Particle Physics in a Season of Change

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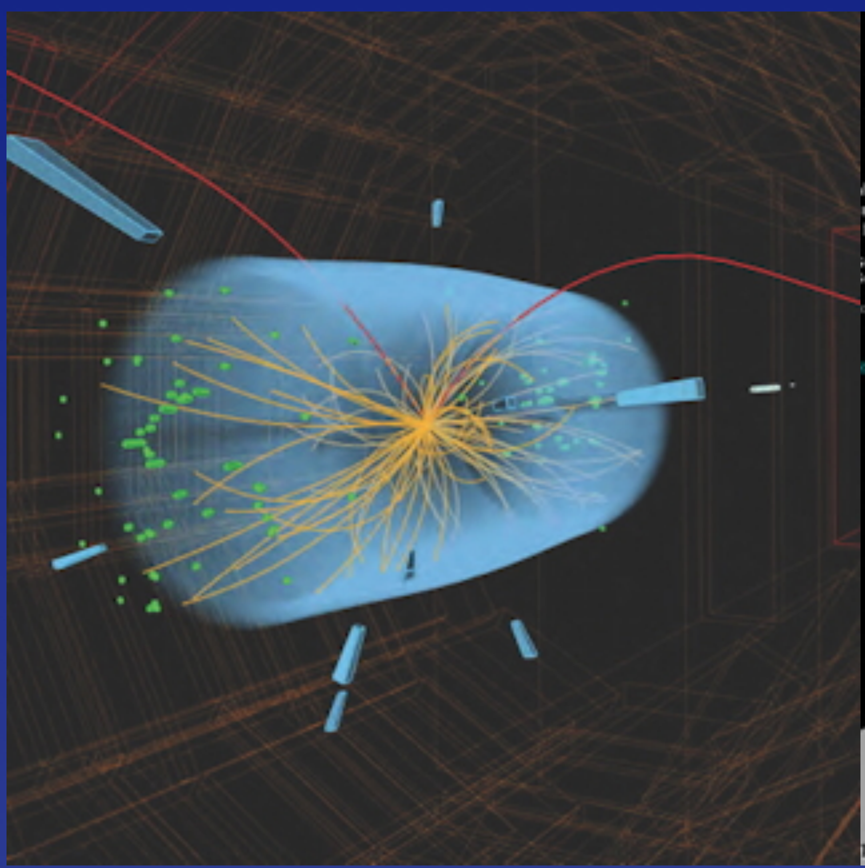
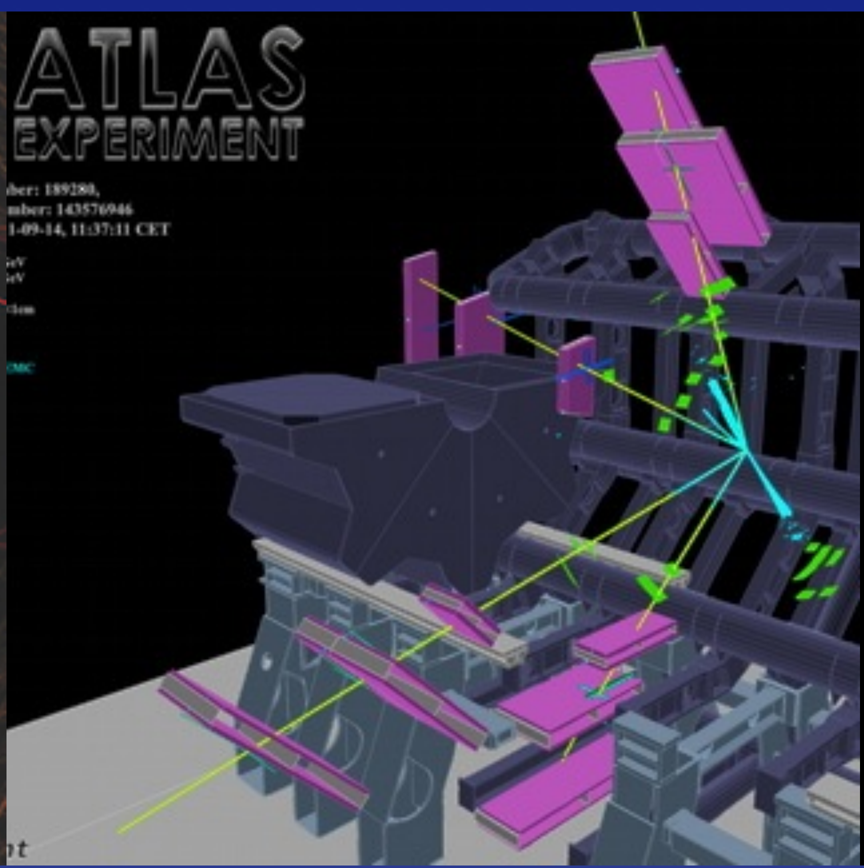
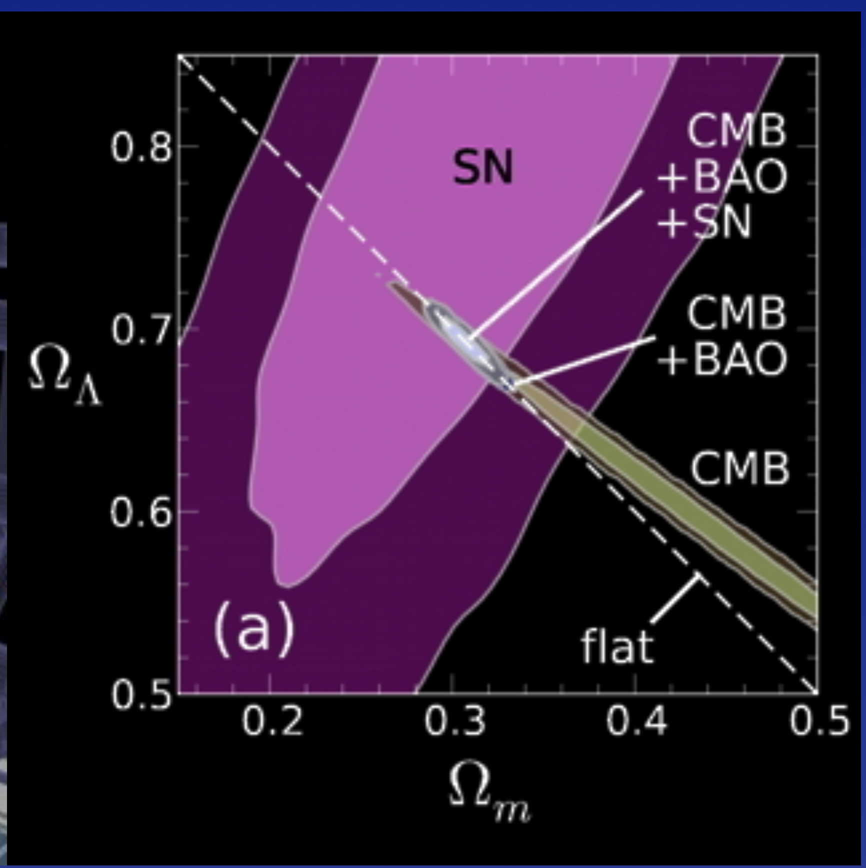
Fermi National Accelerator Laboratory



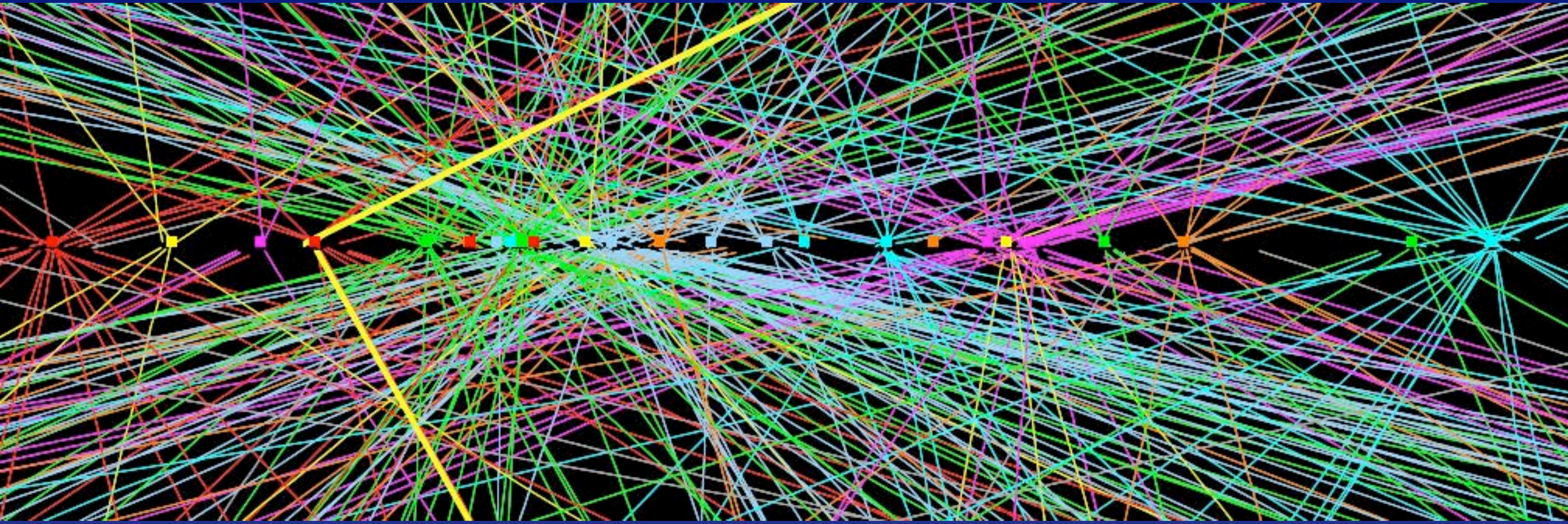




Tufts University · 26 September 2014


Large Hadron Collider
CMS
LHCb
ALICE
ATLAS

Very-High-Rate Experiments

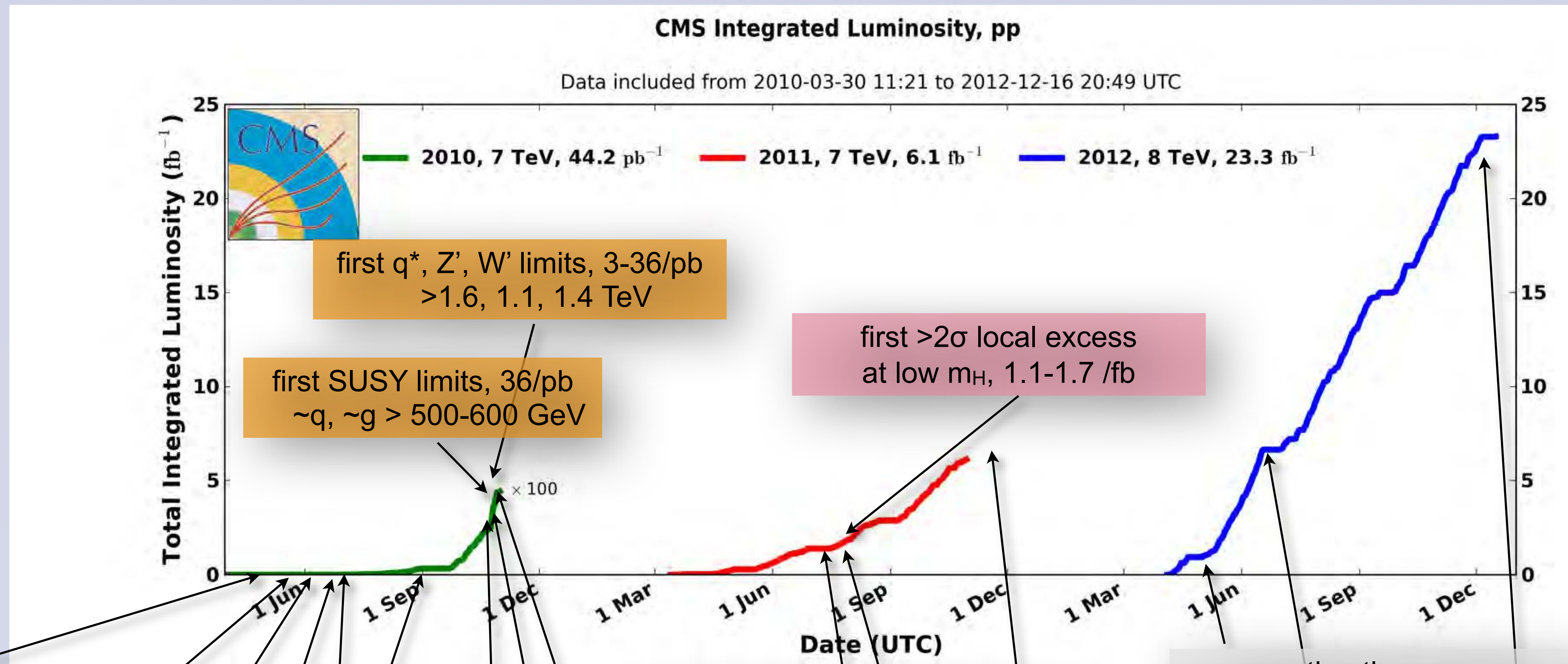


ATLAS

The Allure of Ultrasensitive Experiments

Fermilab Academic Lectures

CMS Experiment Science Progression



first q*, Z', W' limits, 3-36/pb >1.6, 1.1, 1.4 TeV

first SUSY limits, 36/pb ~q, ~g > 500-600 GeV

first >2σ local excess at low m_H, 1.1-1.7 /fb

first MinBias / UE studies, particle multiplicities

first incl. b x-section, 8/nb δ ~ 15 %

first incl. jet x-section, PF jets 60/nb δ ~ 20-30%

first incl. W/Z x-sections, 200/nb δ ~ 4-6%, +11% lumi

first incl. J/Ψ x-section, 100/nb δ ~ 20%

first top xsec, 3/pb δ ~ 40%

first single top xsec, t-chan., 36/pb δ ~ 36%

first m_{top}, 36/pb Δ ~ 6.5 GeV

first WW xsec, 36/pb δ ~ 40% first limit on HWW

first ZZ xsec, 1.1 /fb δ ~ 40%

going more differential, e.g. Z/W + j,b,c

first significant limit on $B_s \rightarrow \mu\mu$, BR<1.9x10^{-8}

first particle discovered by CMS: Ξ_b

BSM searches continue, limits pushed

repeating the program at 8 TeV

a new boson is announced, 5 /fb

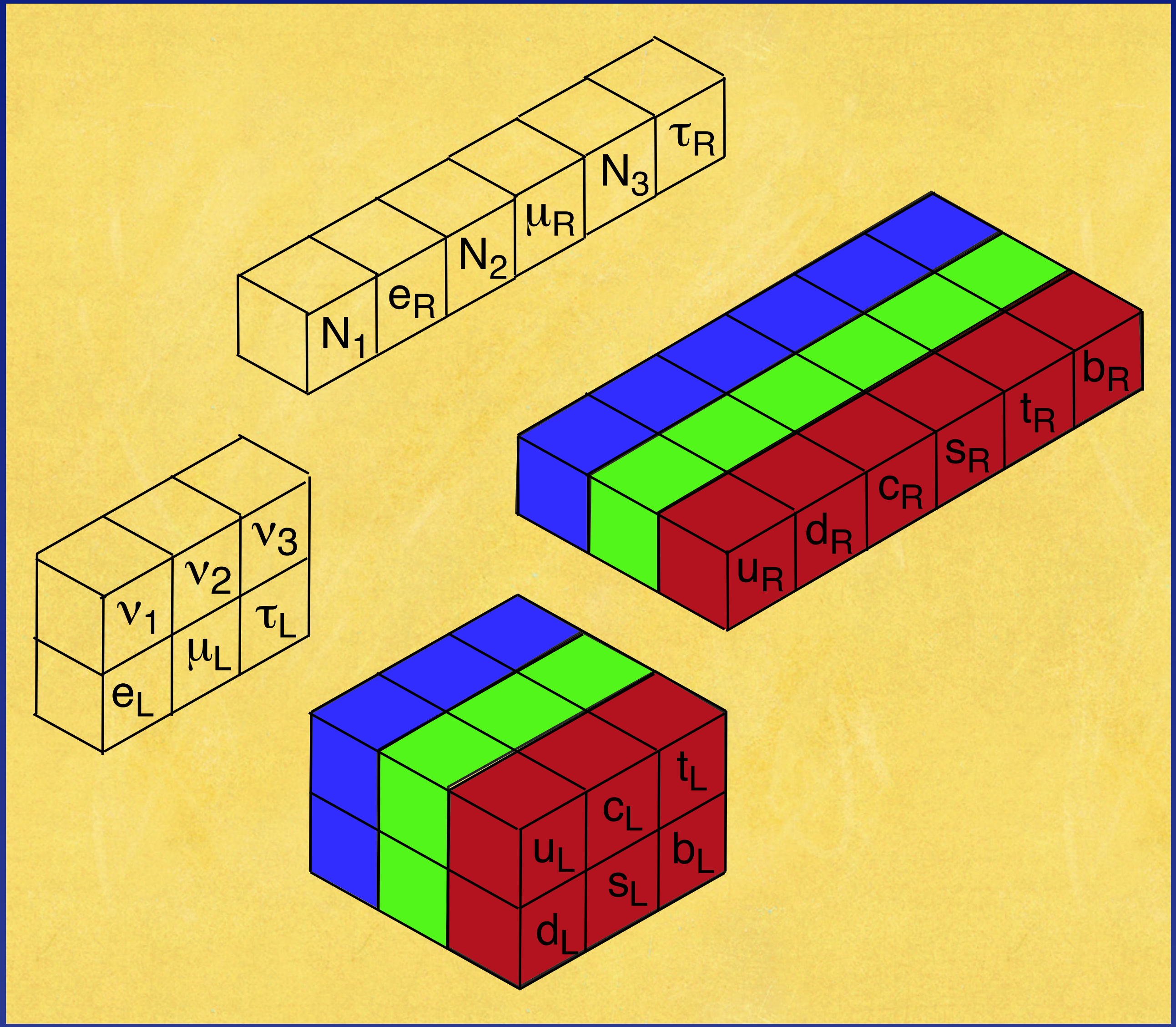
first spin parity analysis of the boson, 17 /fb

δ .. relative uncert   Δ .. absolute uncert.

Before LHC

Two New Laws of Nature +

Pointlike ($r \leq 10^{-18}$ m) *quarks* and *leptons*



Interactions: $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ gauge symmetries

Quantum Chromodynamics

Asymptotically free theory

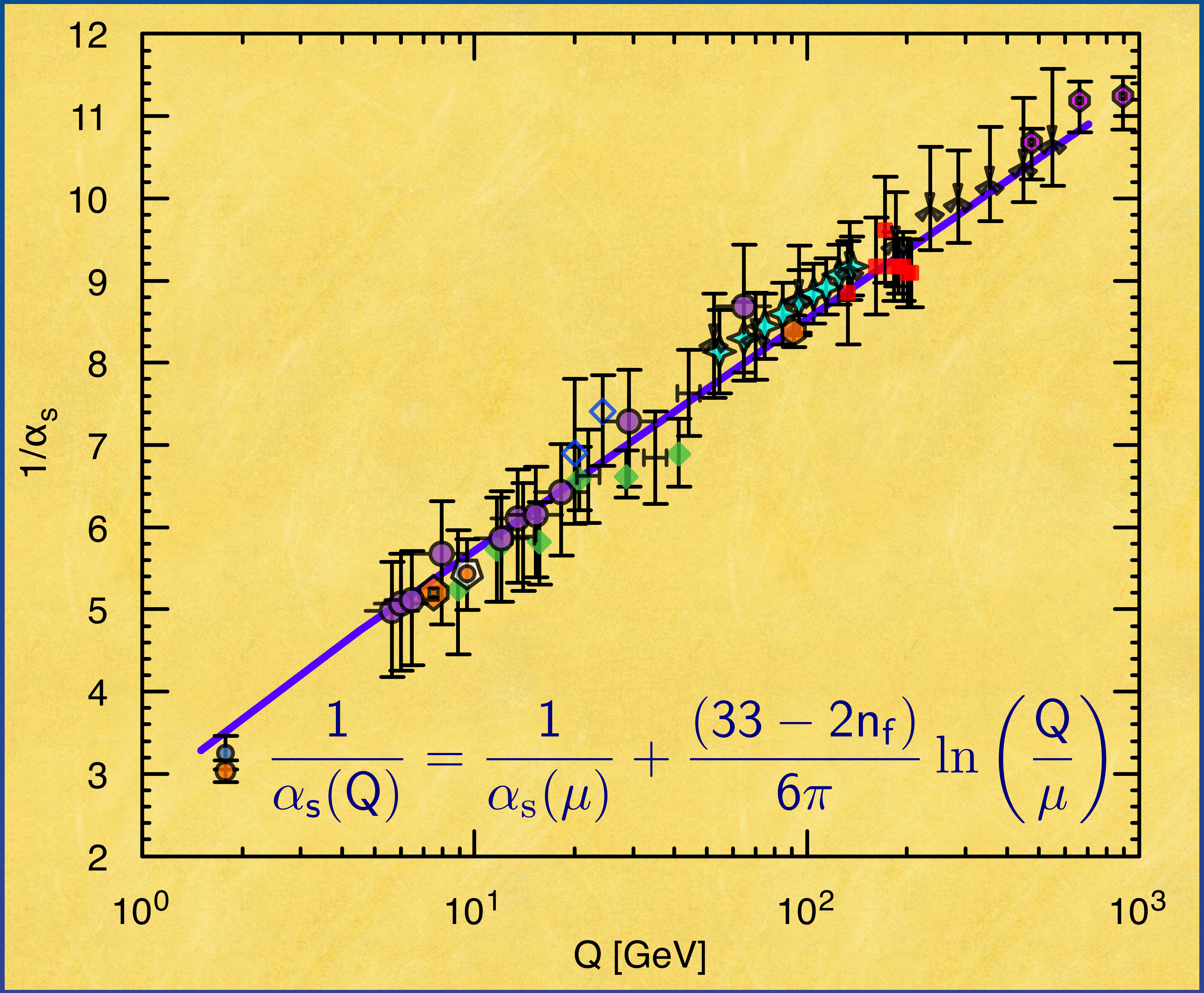
Many successes in perturbation theory to 1 TeV

Growing understanding: nonperturbative regime

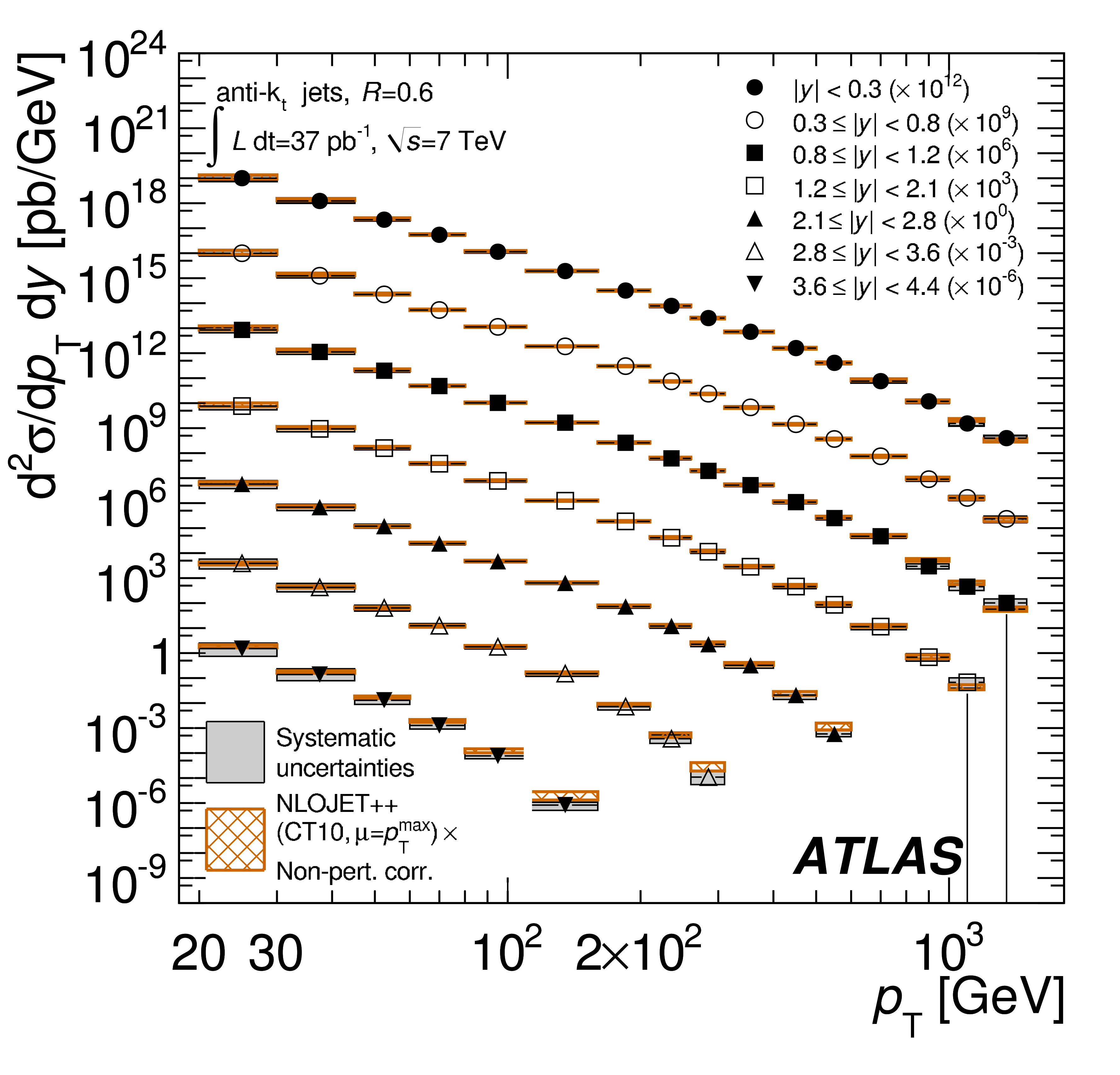
Quarks & gluons confined: evidence, no proof

No structural defects, but *strong CP problem*

Evolution of the strong coupling "constant"

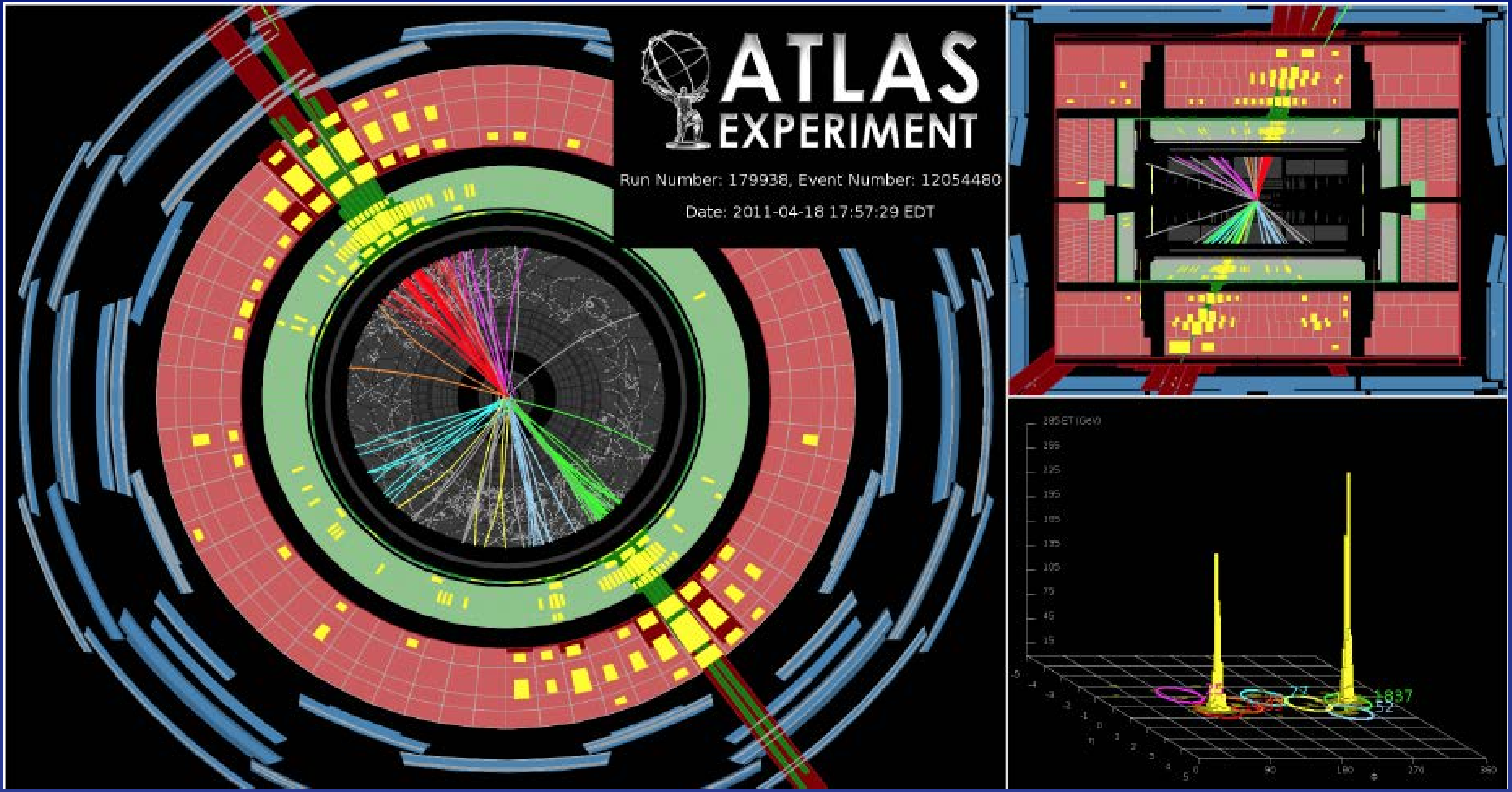


Jet Production



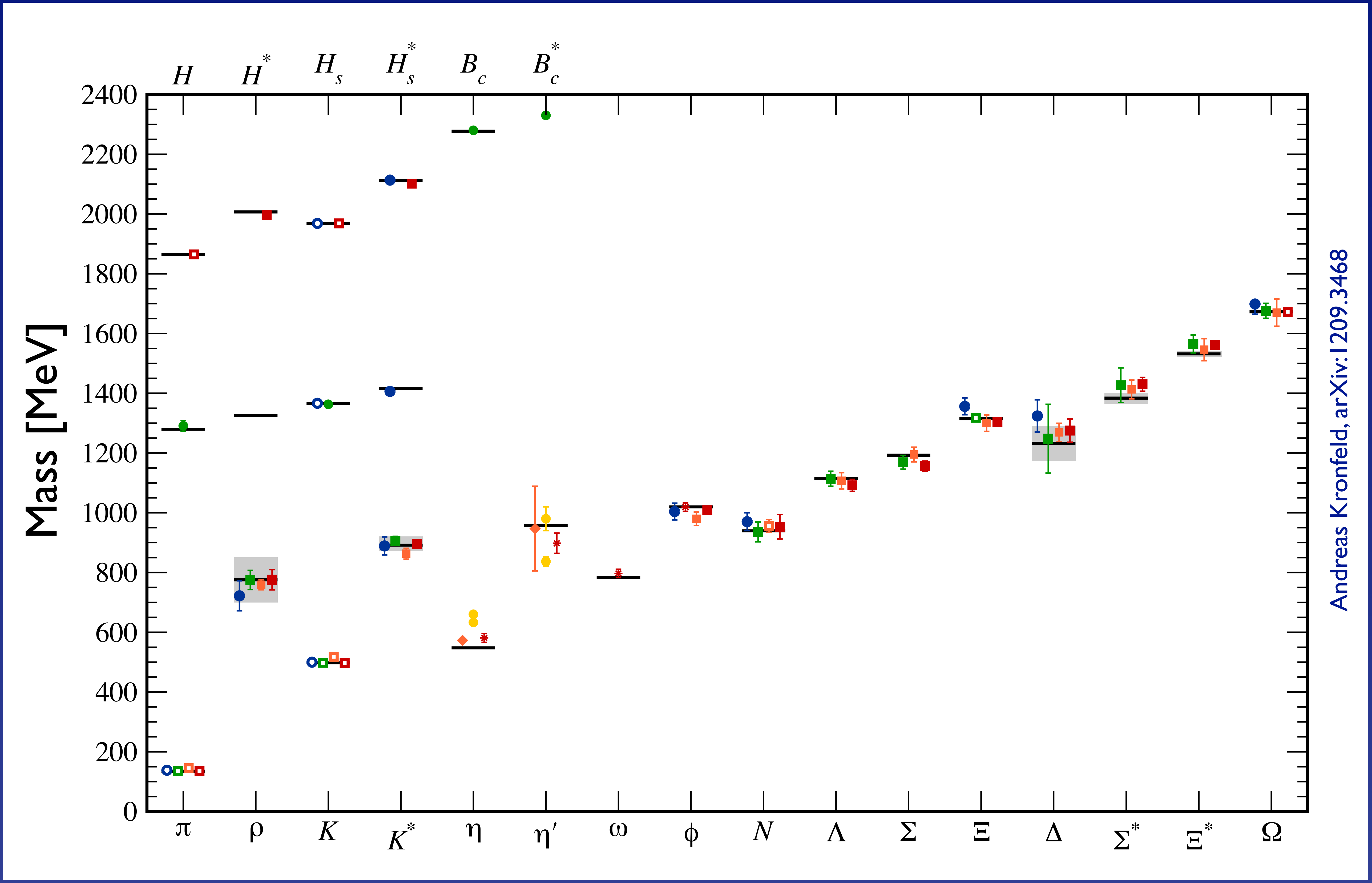
The World's Most Powerful Microscopes

nanonanophysics



Transverse momenta: 1.85 TeV + 1.84 TeV · *Dijet mass:* 4.04 TeV

Hadron masses from (2+1)-flavor LQCD



sum of parts

rest energy

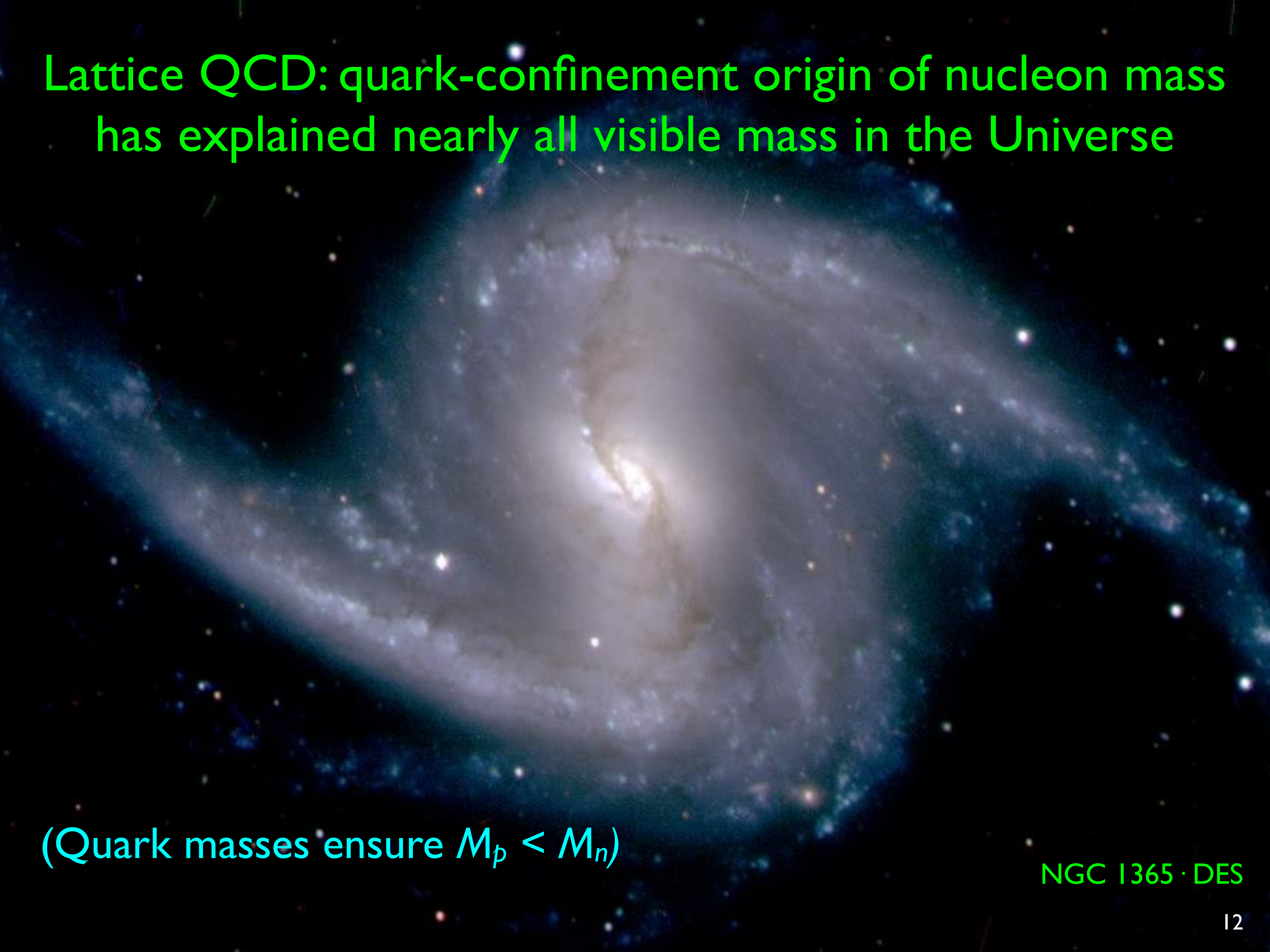
Nucleon mass: exemplar of $m = E_0/c^2$

up and down quarks contribute few %

$$3\,\frac{m_u + m_d}{2} = 10 \pm 2 \text{ MeV}$$

χPT: $M_N \hookrightarrow$ 870 MeV for massless quarks

Lattice QCD: quark-confinement origin of nucleon mass has explained nearly all visible mass in the Universe



(Quark masses ensure $M_p < M_n$)

NGC 1365 · DES

QCD could be complete, up to M_{Planck}

… but that doesn't prove it must be

Prepare for surprises!

How might QCD Crack?

(Breakdown of factorization)
Free quarks / unconfined color
New kinds of colored matter
Quark compositeness
Larger color symmetry containing QCD

New phenomena within QCD?

Multiple production beyond diffraction + short-range order?

High density of few-GeV partons … thermalization?

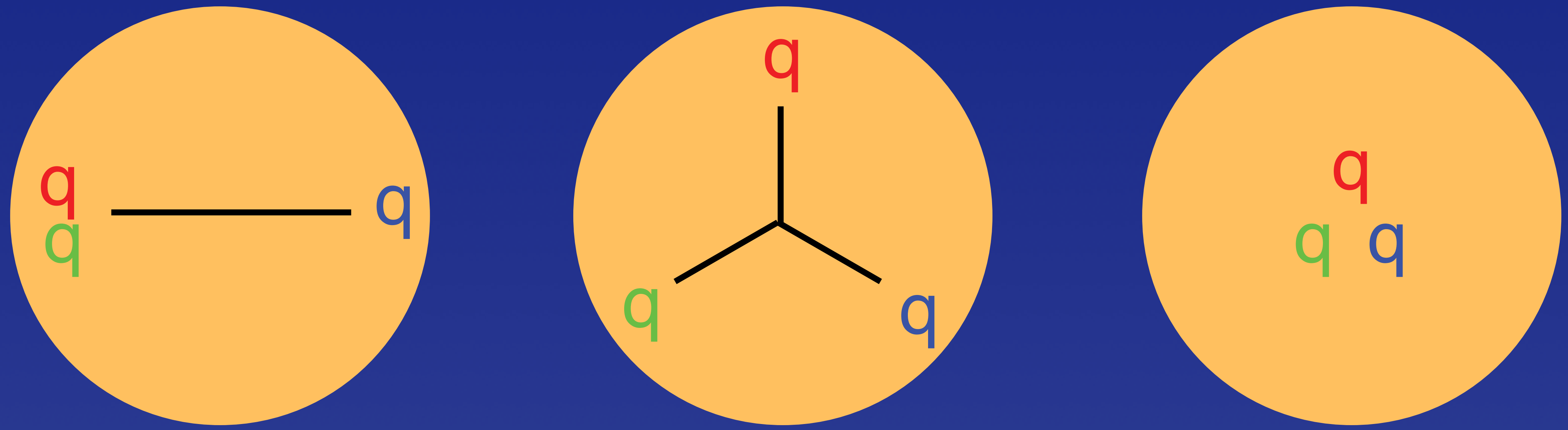
Long-range correlations in y?

Unusual event structures …

Look at events in informative coordinates.
More is to be learned from the river of events than from a few specimens!

Correlations among the partons?

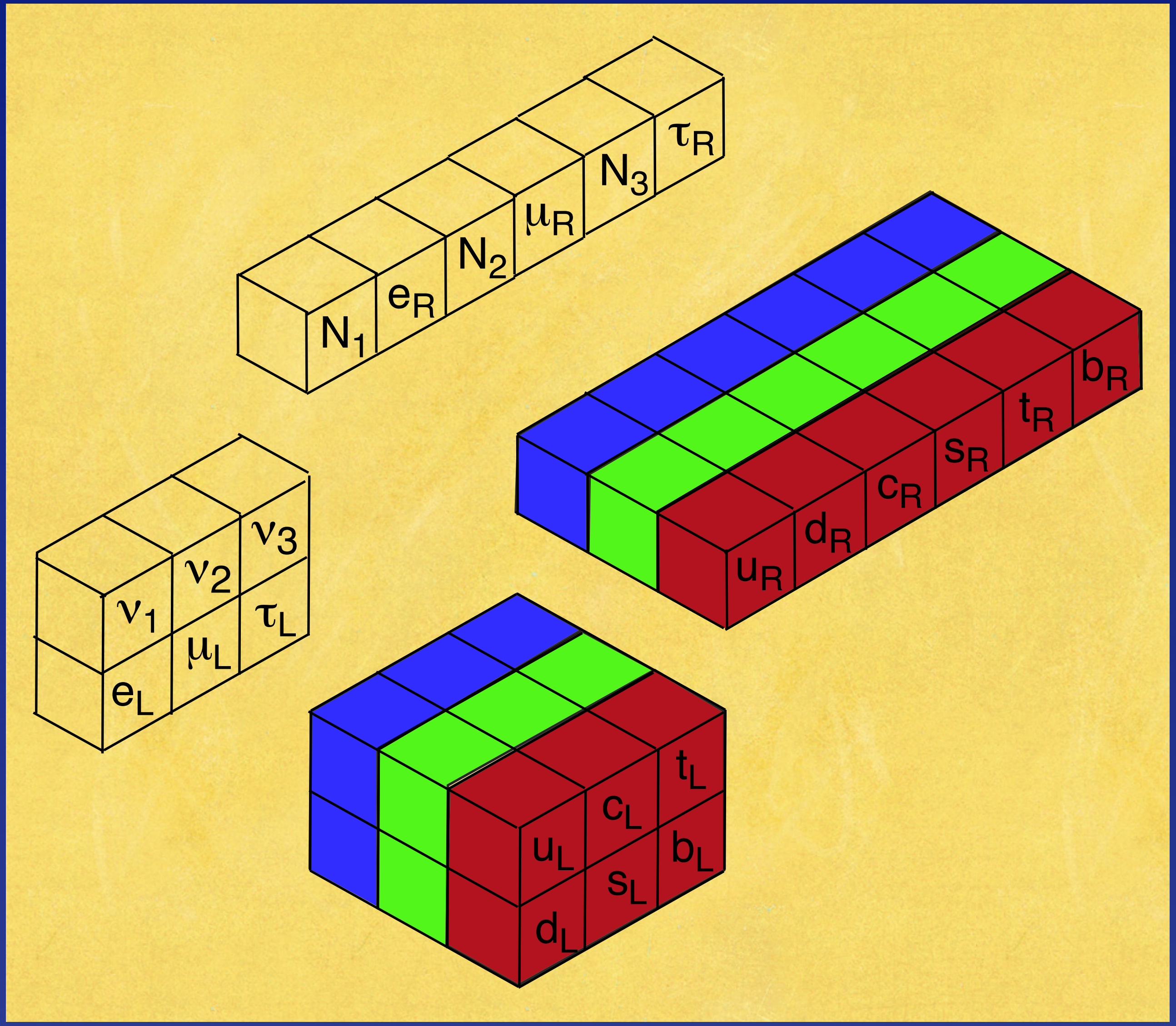
A proton knows it is a proton.
Single-spin asymmetries imply correlations.
What else?



Bjorken (2010)

Can we distinguish different configurations?
Interplay with multiple-parton interactions?

Electroweak Symmetry Breaking



$U(1)_{EM}$

Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

Electroweak Theory

To good approximation …

3-generation V–A charged currents

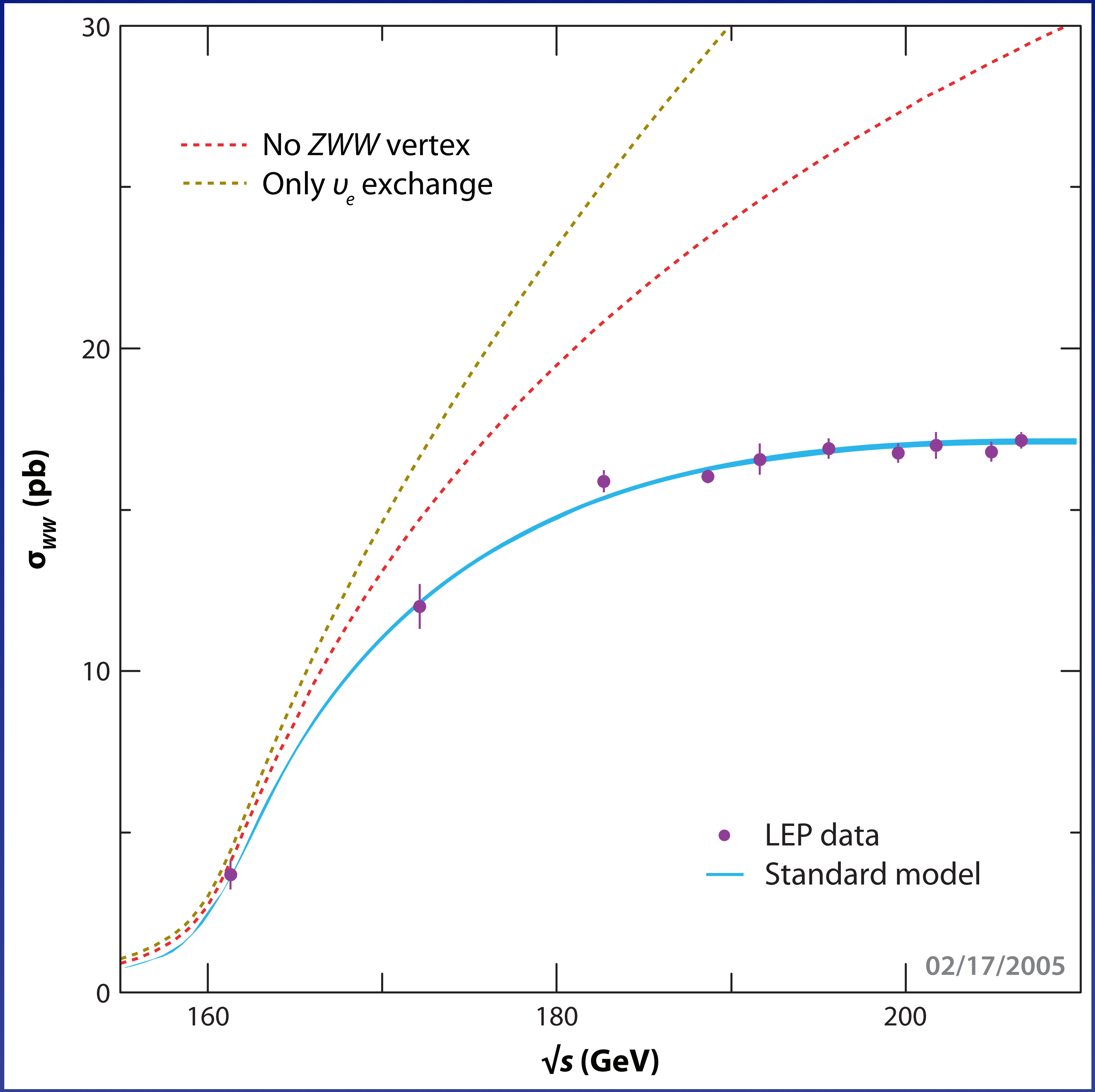
GIM suppresses flavor-changing neutral currents

CKM quark-mixing matrix describes CP violation

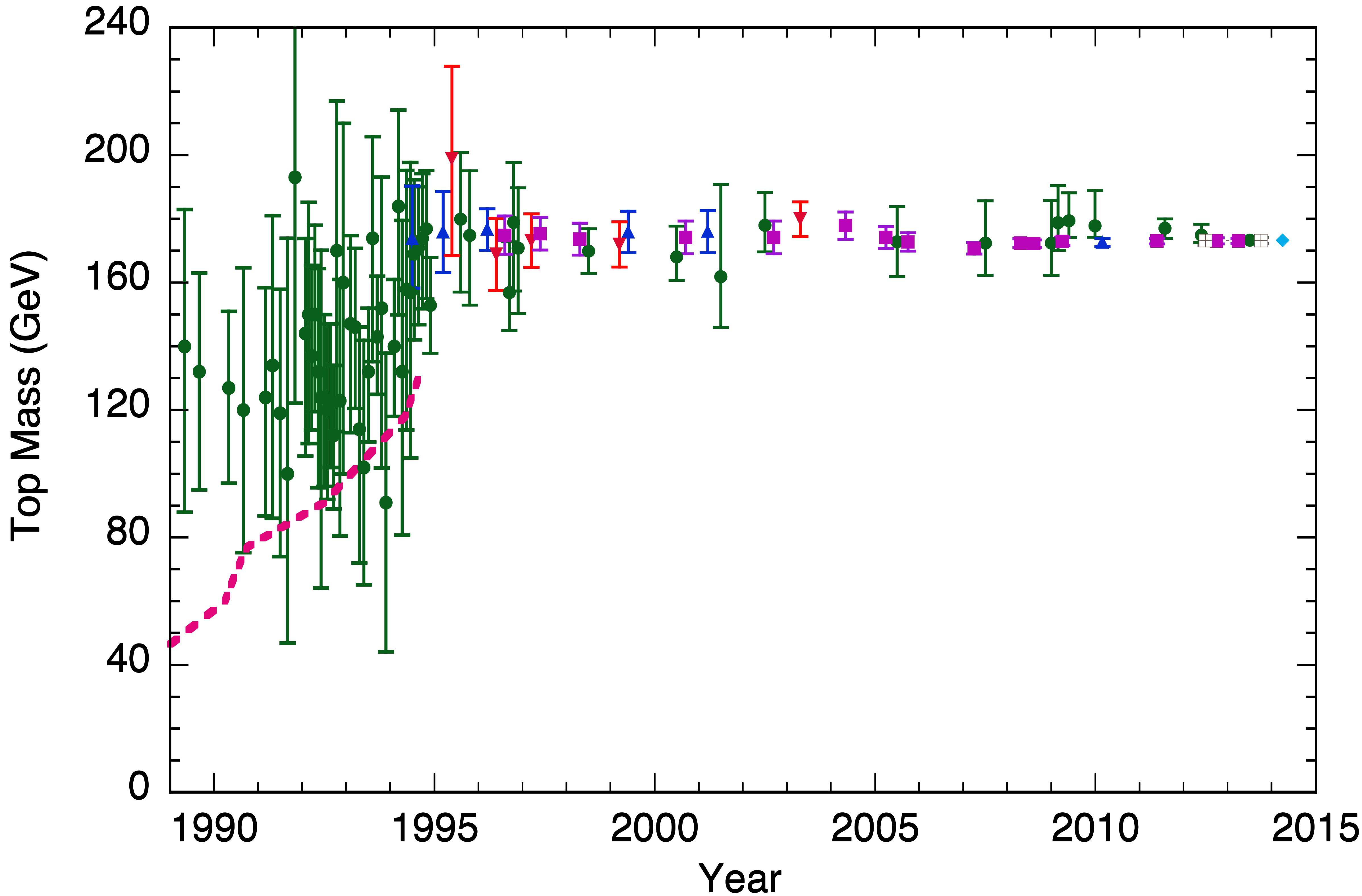
Tested as quantum field theory at per-mille level

Gauge symmetry validated in $e^+e^- \to W^+W^-$

LEP validated secret SU(2)$_L$⊗U(1)$_Y$ symmetry



Electroweak theory anticipates discoveries



A hitherto unknown agent hides electroweak symmetry

- ✳ A force of a new character, based on interactions of an elementary scalar
- ✳ A new gauge force, perhaps acting on undiscovered constituents
- ✳ A residual force that emerges from strong dynamics among electroweak gauge bosons
- ✳ An echo of extra spacetime dimensions

The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

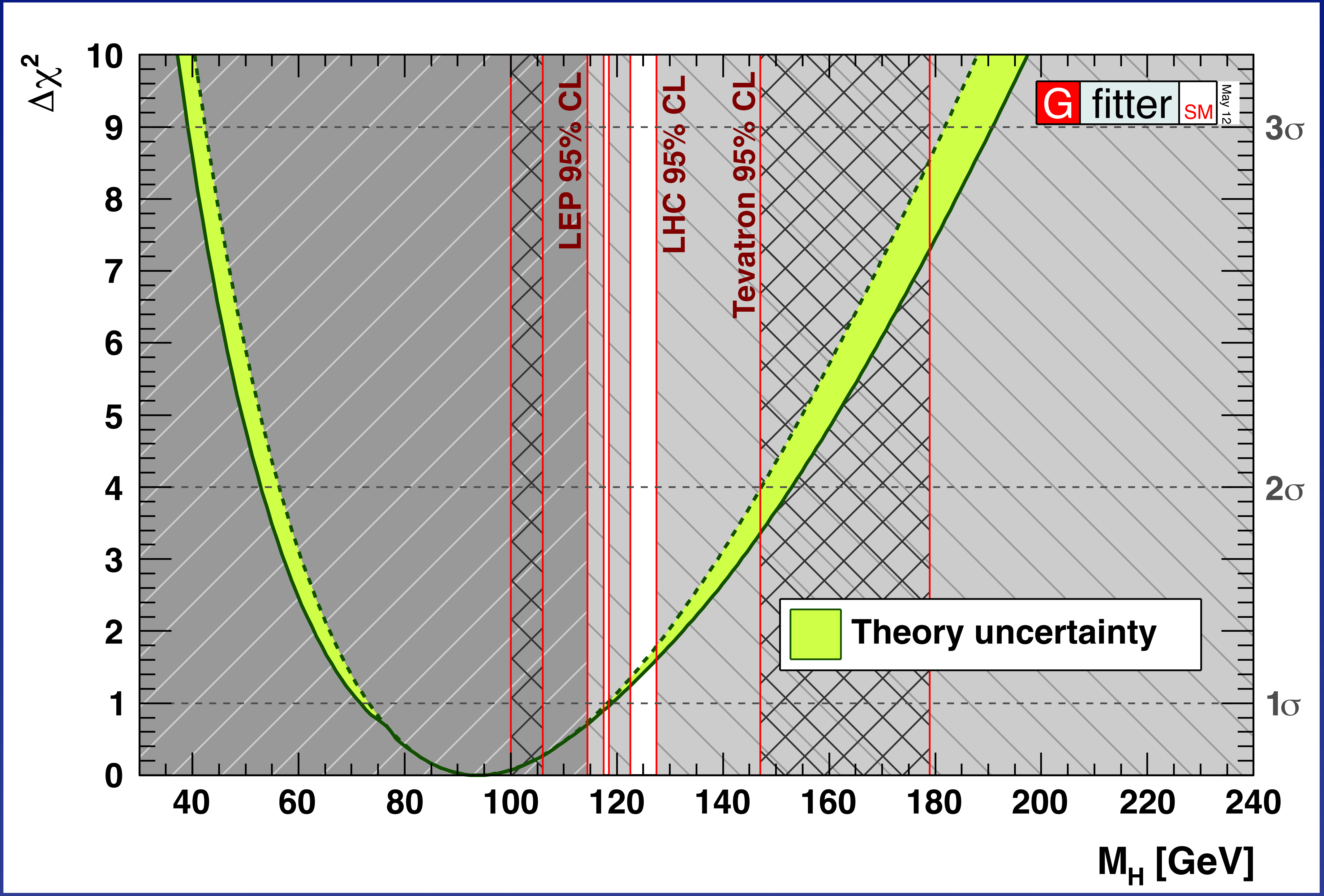
W^+W^-, ZZ, HH, HZ satisfy s-wave unitarity,

provided $\boxed{M_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1\ \text{TeV}}$

- If bound is respected, perturbation theory is "everywhere" reliable
- If not, weak interactions among $W^\pm$, Z, H become strong on 1-TeV scale

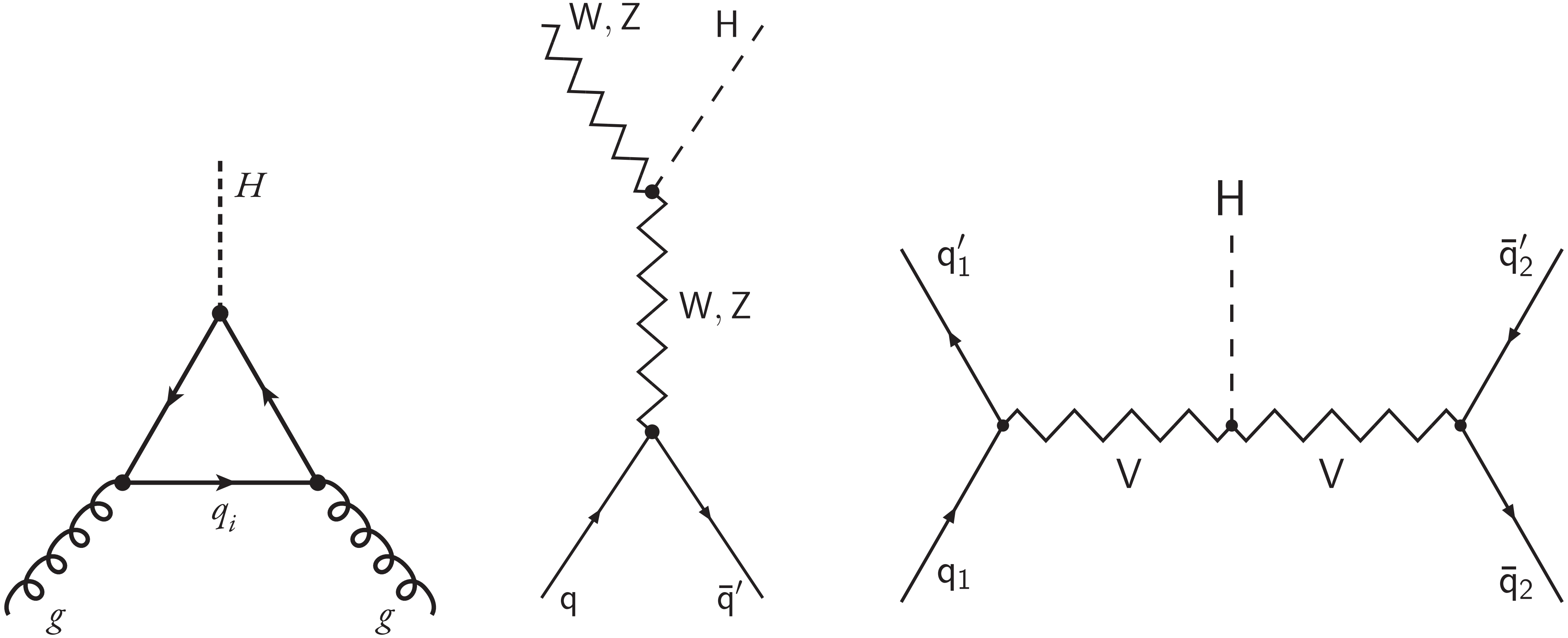
New phenomena are to be found around 1 TeV

H couplings to *W*, *Z* tested indirectly



Beyond standard model: heavy Higgs allowed, even natural

LHC can search in many channels

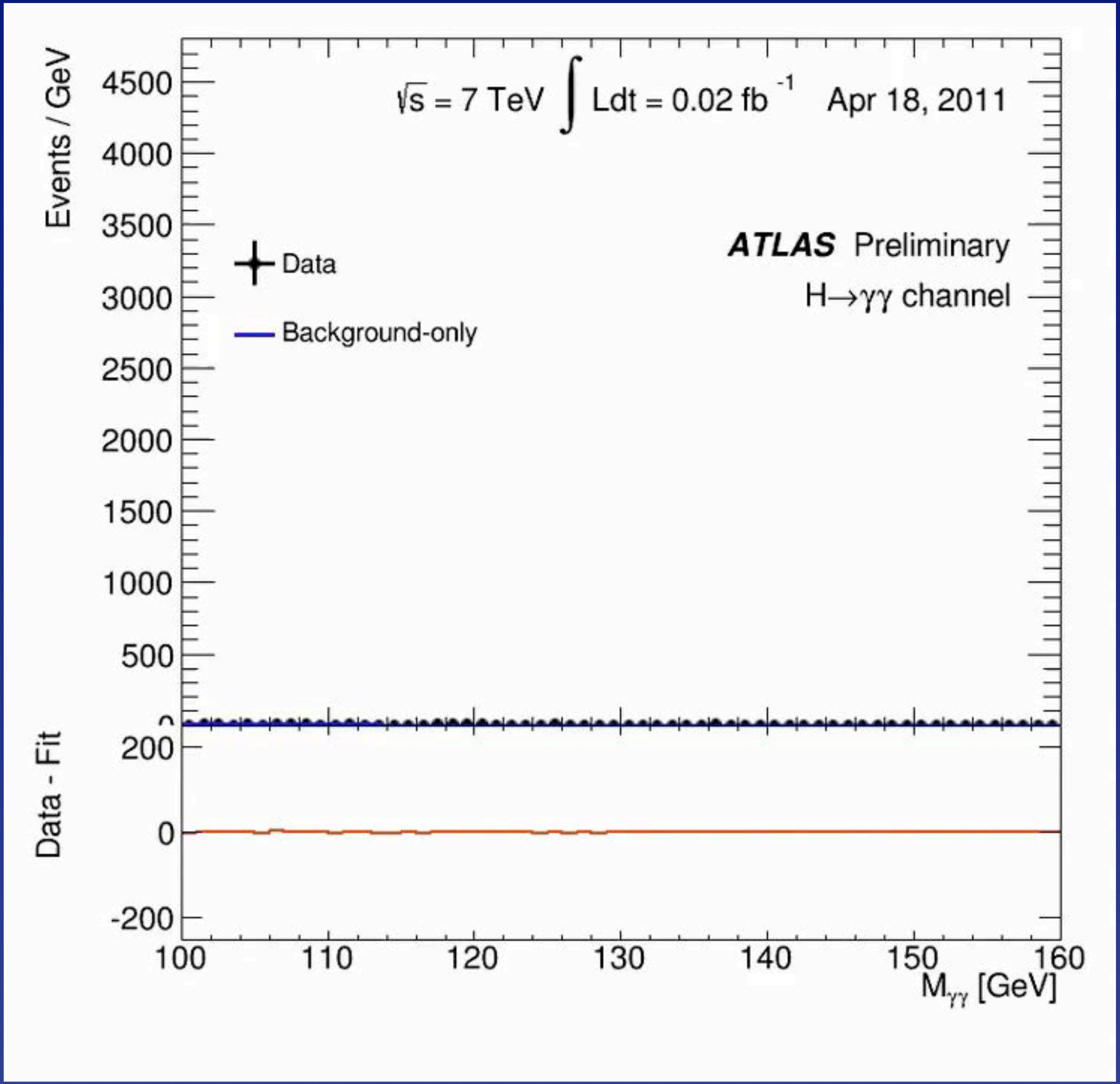


+ $Ht\bar{t}$

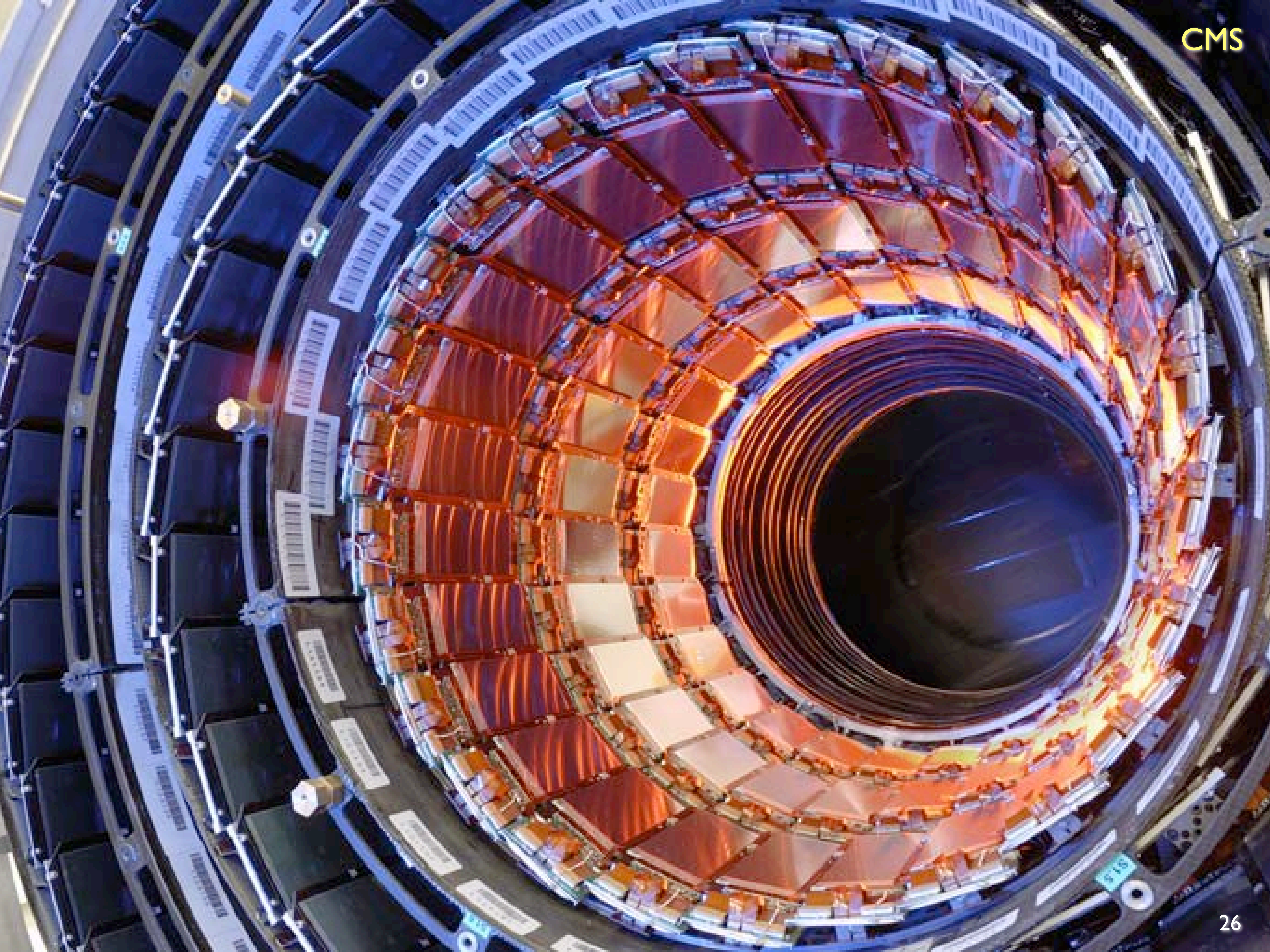
$\gamma\gamma$, WW^*, ZZ^*, $\tau^+\tau^-$, b pairs, …

ATLAS-inspired
Les Troyens (Valencia)

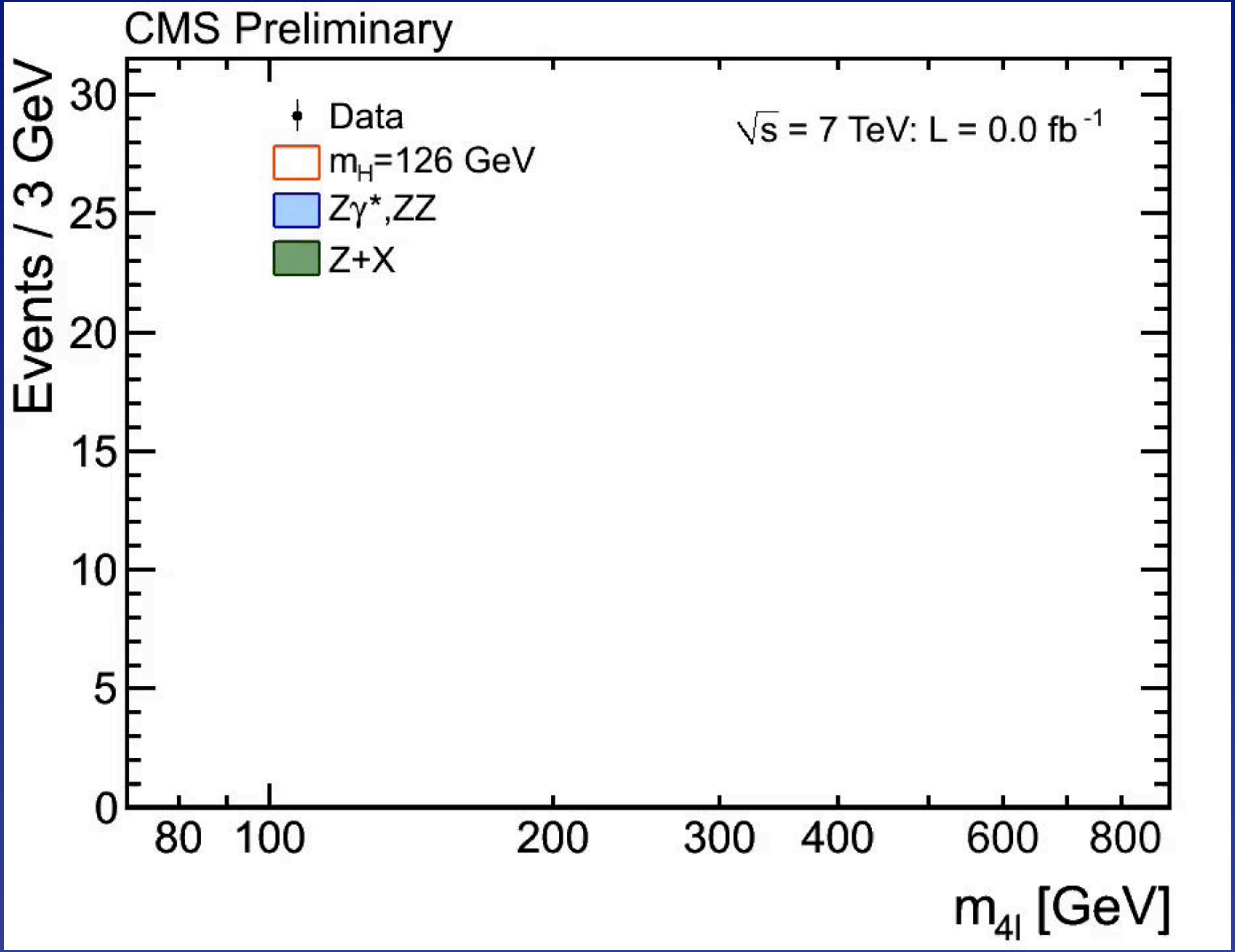
Evolution of ATLAS γγ Signal



CMS



Evolution of CMS 4-lepton Signal



Evolution of evidence at the LHC

Evidence is developing as it would for
a "standard-model" Higgs boson

Unstable neutral particle near 125 GeV

ATLAS: $M_H = 125.36 \pm 0.37$ (stat) $\pm\, 0.18$ (syst) GeV

CMS: $M_H = 125.03^{+0.26}_{-0.27}$ (stat) ${}^{+0.13}_{-0.15}$ (syst) GeV

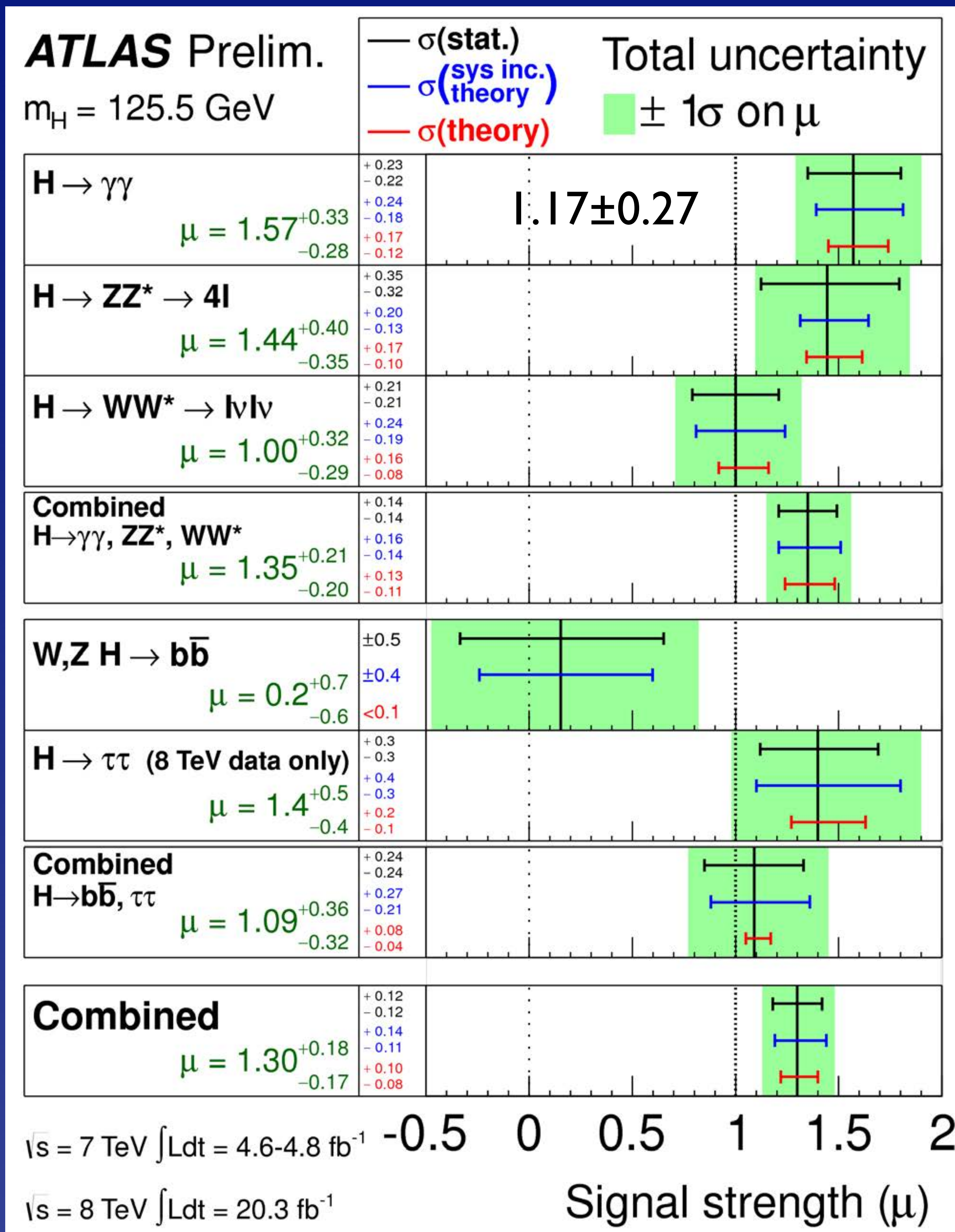
decays to $\gamma\gamma, W^+W^-, ZZ$

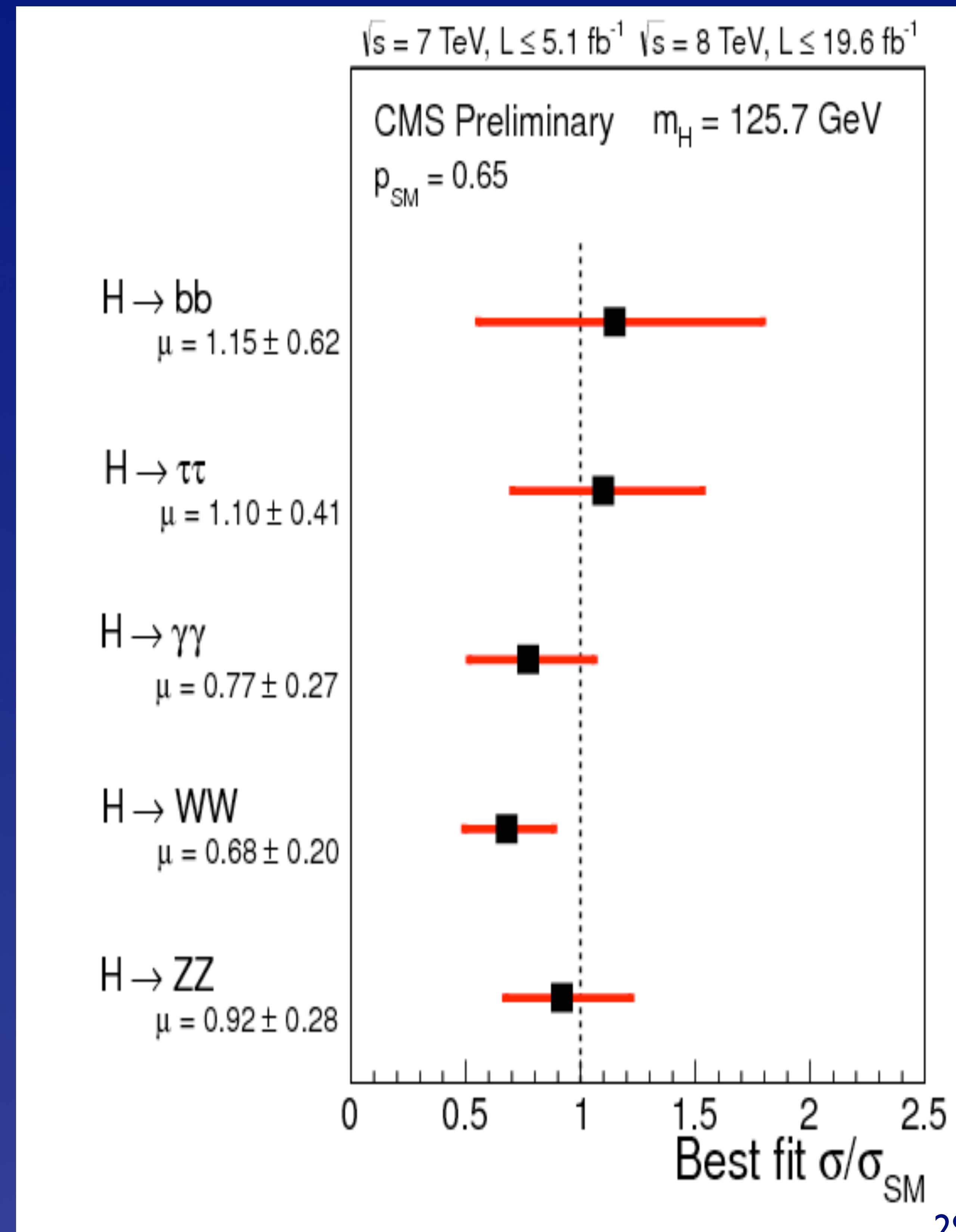
likely spin-parity 0^+

evidence for $\tau^+\tau^-, b\bar{b}$; $t\bar{t}$ from production

only third-generation fermions tested

ATLAS Signal / Standard Model CMS





Why does discovering the agent matter?

Imagine a world without a symmetry-breaking (Higgs) mechanism at the electroweak scale

Electron and quarks would have no mass

QCD would confine quarks into protons, etc.

Nucleon mass little changed

Surprise: QCD would hide EW symmetry, give tiny masses to W, Z

Massless electron: atoms lose integrity

No atoms means no chemistry, no stable composite structures like liquids, solids, …

… no template for life.

arXiv:0901.3958

Fully accounts for EWSB (W, Z couplings)?

Couples to fermions?

Top from production,

need direct observation for b, τ

Accounts for fermion masses?

Fermion couplings $\propto$ masses?

Are there others?

Quantum numbers? ($J^P = 0^+$)

SM branching fractions to gauge bosons?

Decays to new particles?

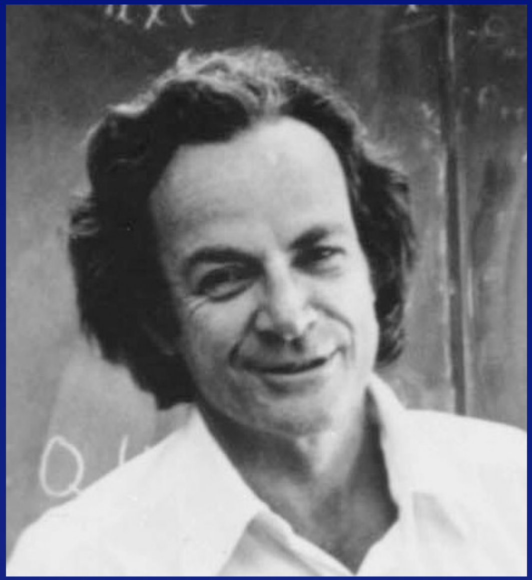
All production modes as expected?

Implications of $M_H \approx 125$ GeV?

Any sign of new strong dynamics?

Parameters of the Standard Model

3	coupling parameters $\alpha_s, \alpha_{\mathrm{em}}, \sin^2\theta_W$
2	parameters of the Higgs potential
1	vacuum phase (QCD)
6	quark masses
3	quark mixing angles
1	CP-violating phase
3	charged-lepton masses
3	neutrino masses
3	leptonic mixing angles
1	leptonic CP-violating phase $(+$ Majorana $\ldots)$
26^+	arbitrary parameters



Why does the muon weigh?

gauge symmetry allows

$$\zeta_e \left[(\bar{e}_L \Phi) e_R + \bar{e}_R (\Phi^\dagger e_L)\right] \rightsquigarrow m_e = \zeta_e v/\sqrt{2}$$

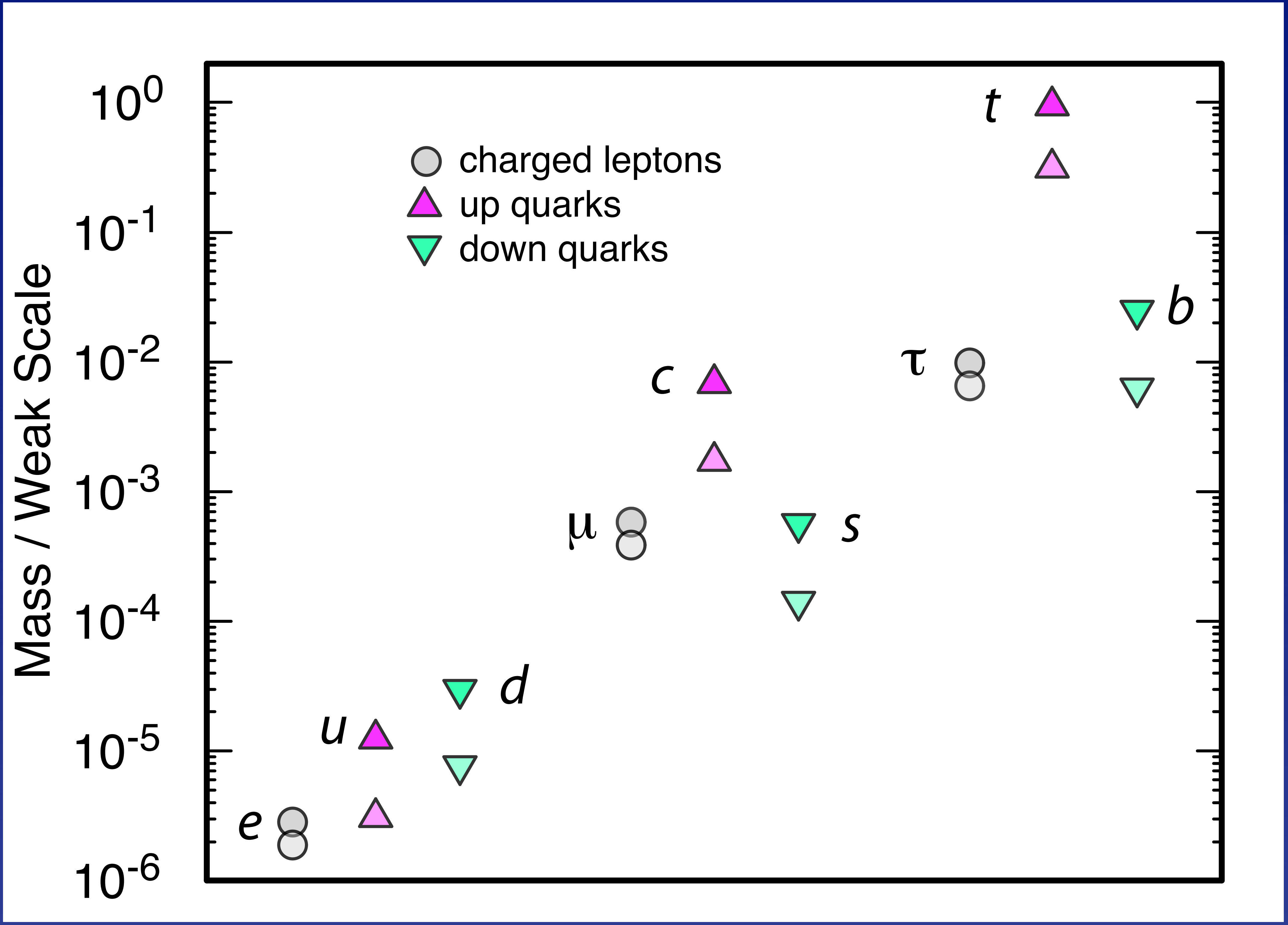
after SSB

What does the muon weigh?

ζ_e : picked to give right mass, not predicted

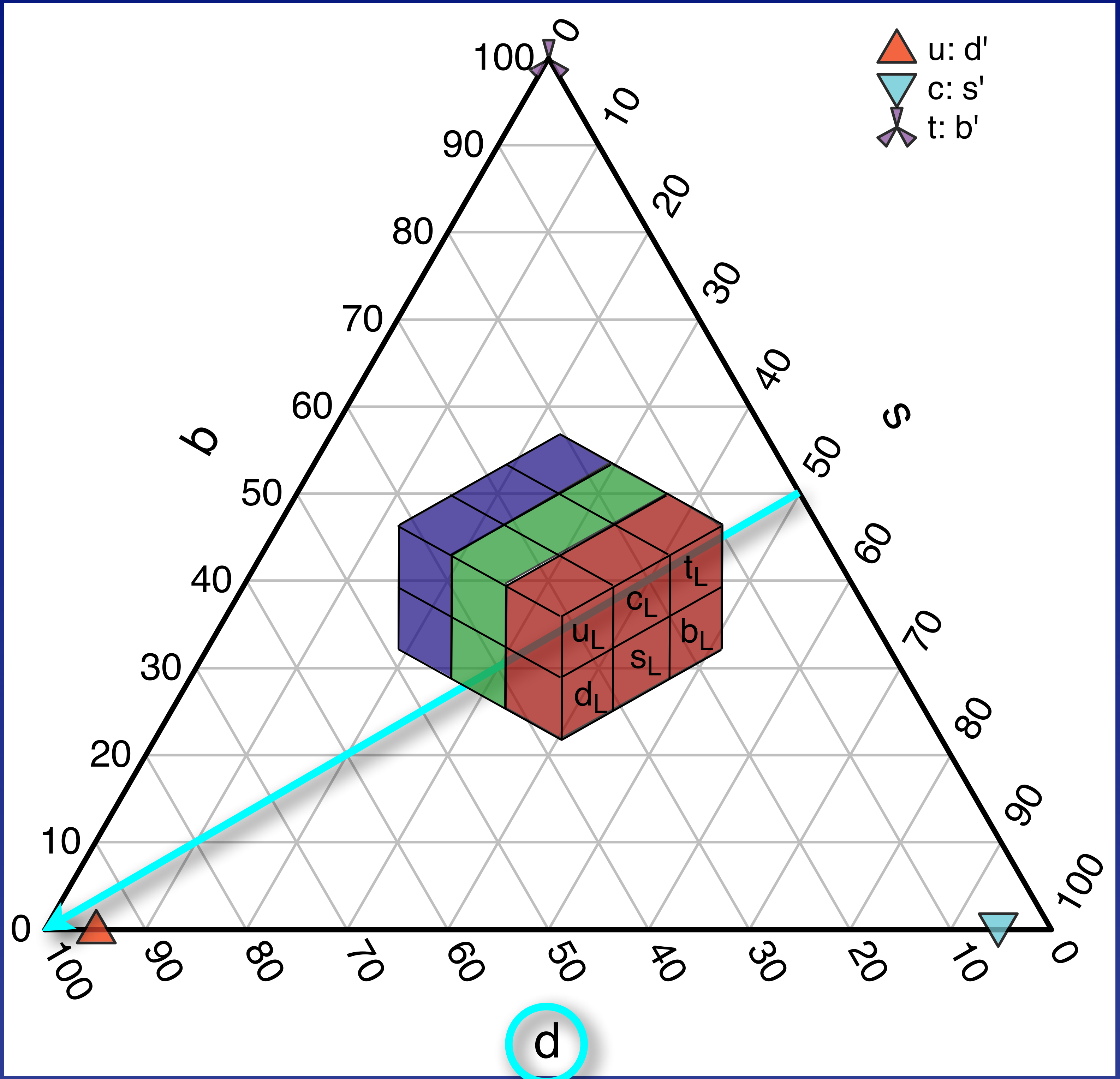
fermion mass implies physics beyond the standard model

Charged Fermion Masses



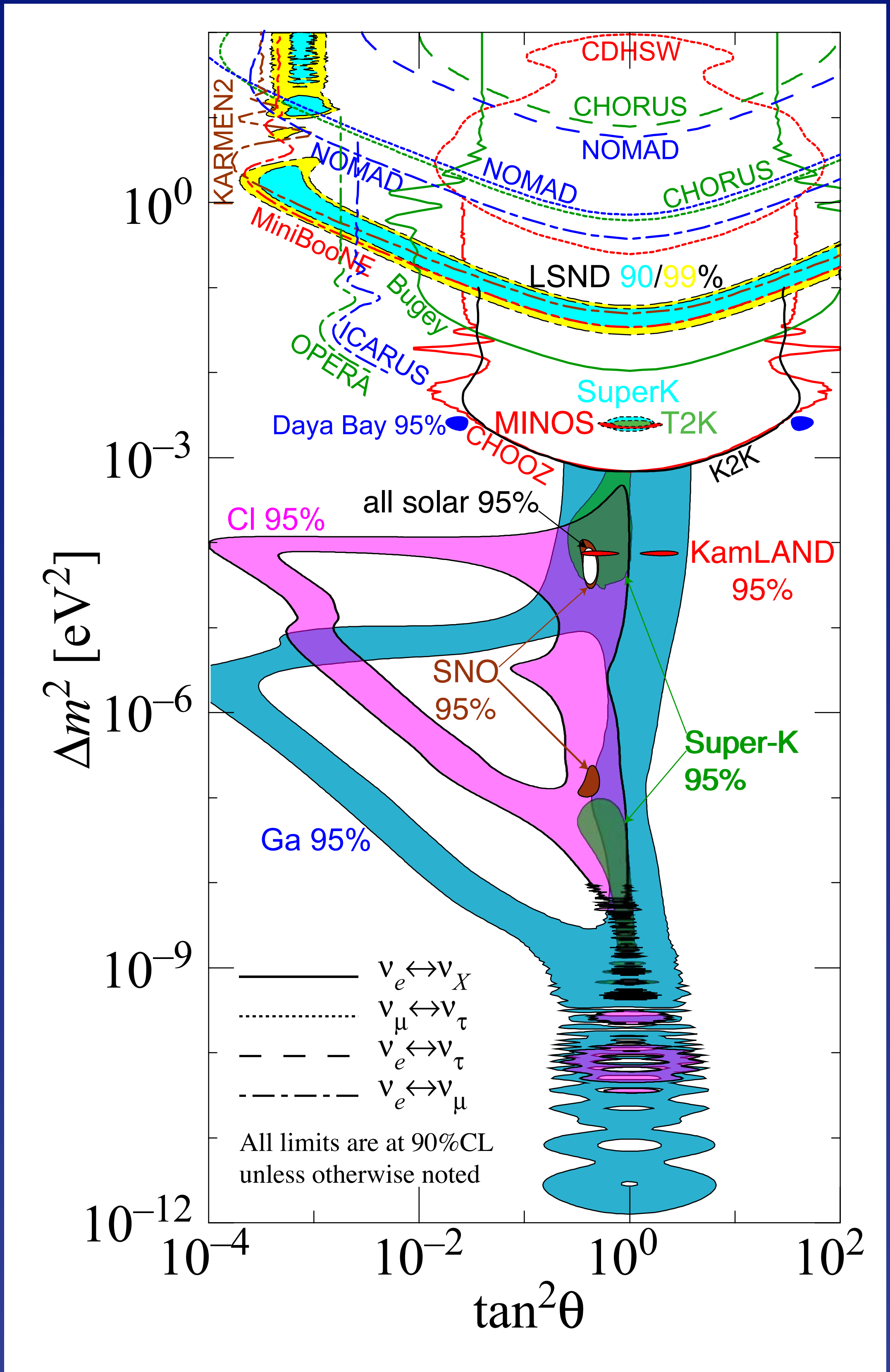
Running mass $m(m)$ … $m(U)$

Quark family patterns: *generations*

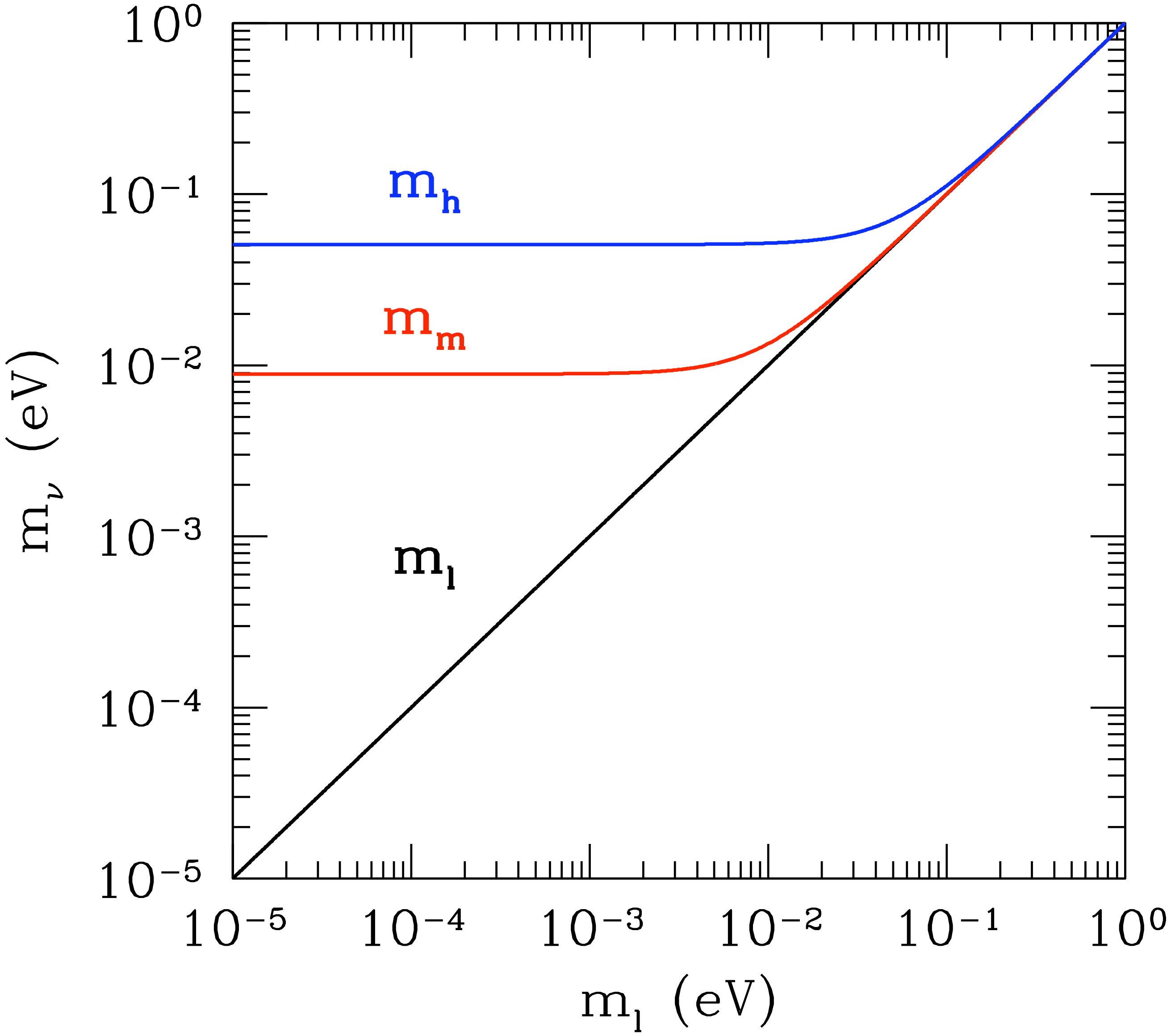


Veltman: Higgs boson knows something we don't know!

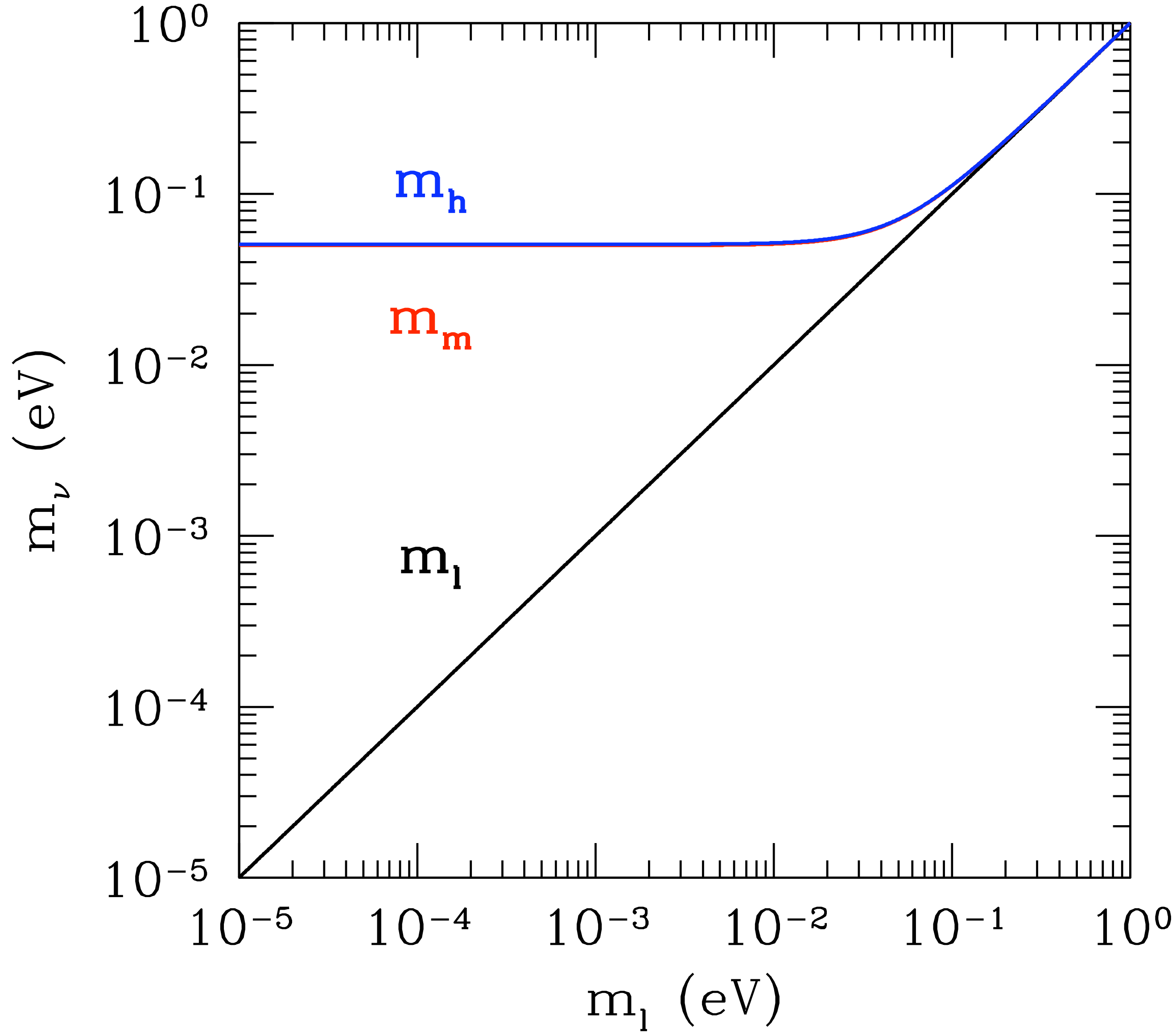
Neutrino Masses and Mixings



Neutrino Masses

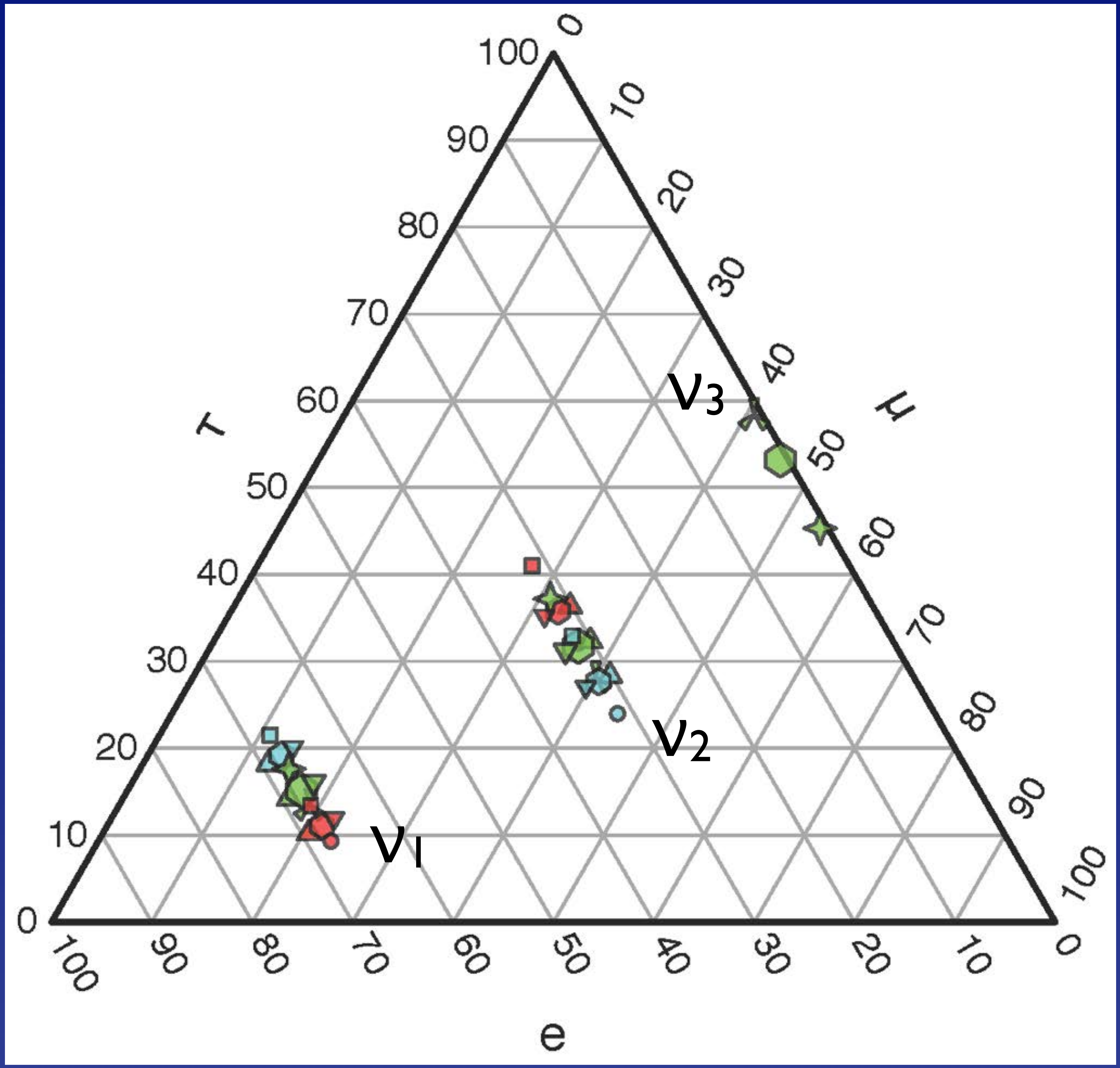


Normal: light solar pair



Inverted: heavy solar pair

Neutrino family patterns



Will the fermion masses and mixings reveal symmetries or dynamics or principles?

What is CP violation trying to tell us?

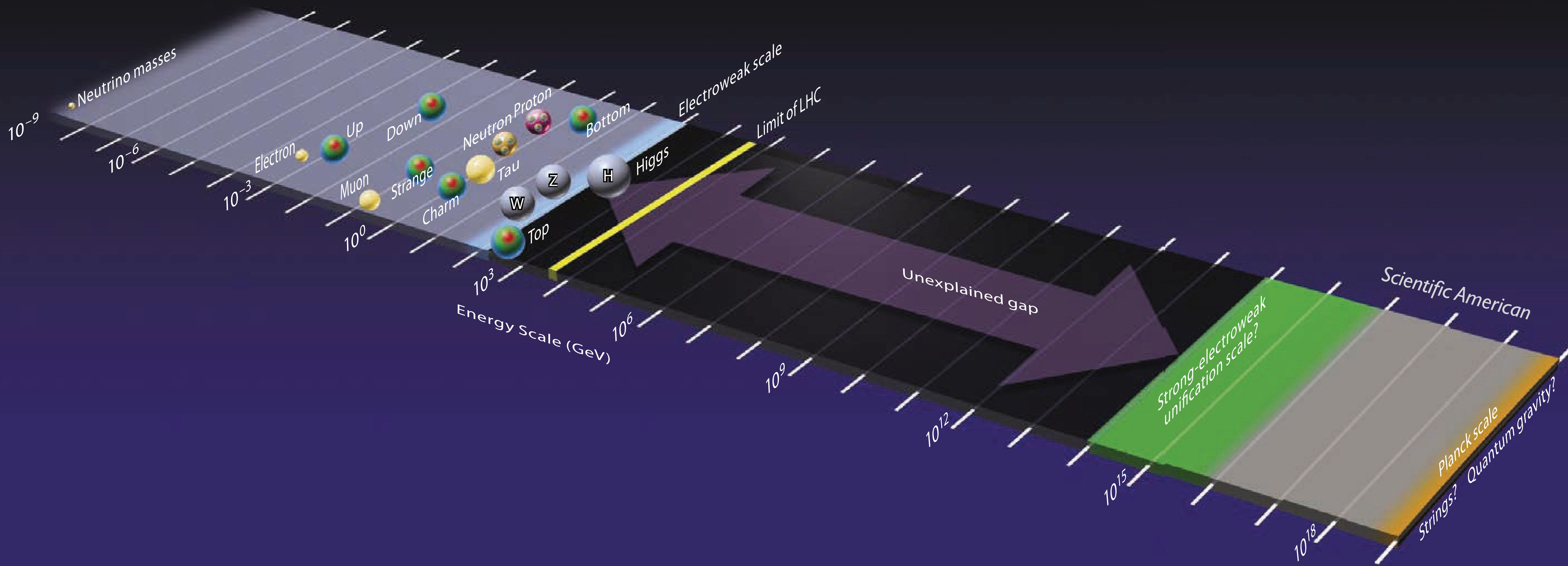
Some questions now seem to us the wrong questions:
Kepler's obsession – Why six planets in those orbits?

Landscape interpretation as environmental parameters

Might still hope to find equivalent of Kepler's Laws!

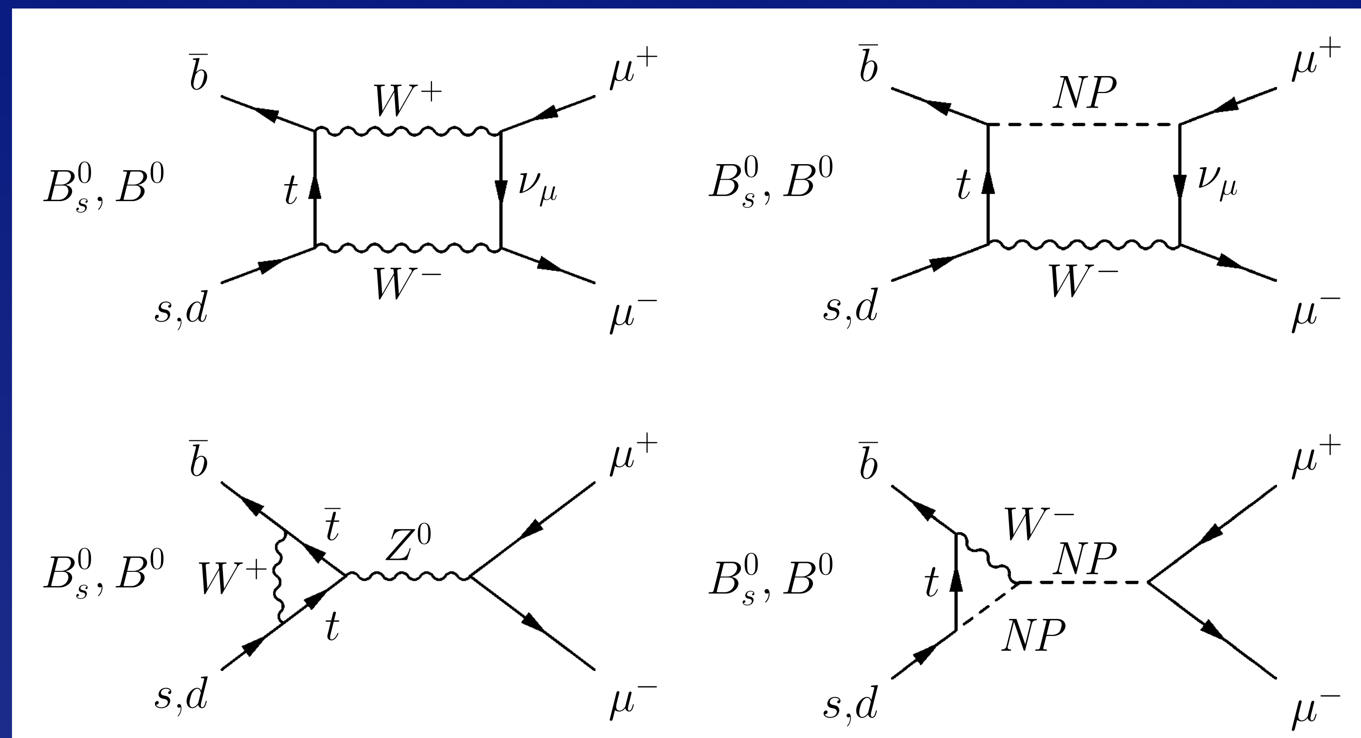
Does $M_H \approx 125$ GeV make sense?

The peril of quantum corrections



Great interest in searches for forbidden or suppressed processes

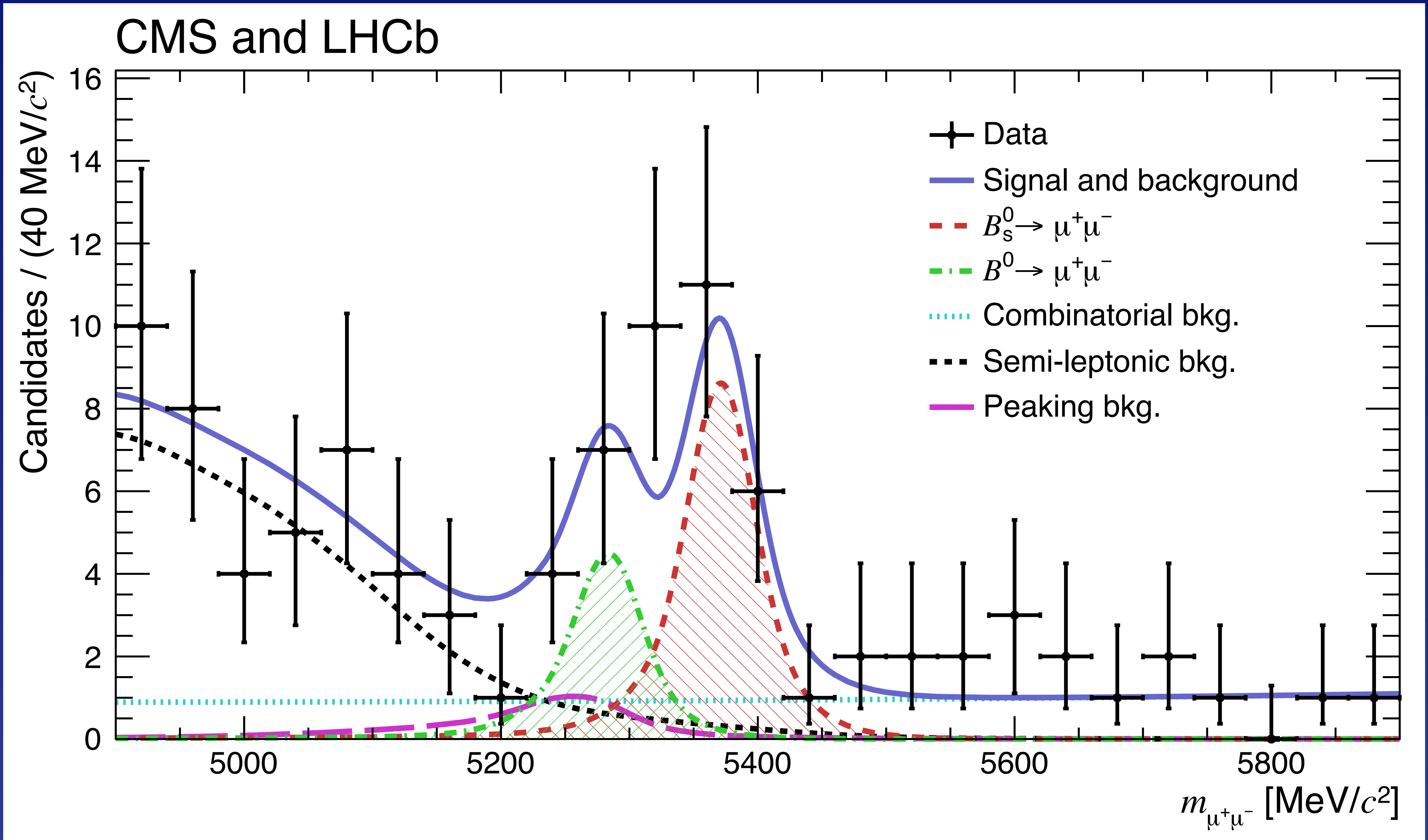
Rare Processes: Flavor-changing neutral currents



$$\text{SM: } \mathrm{BR}(\mathrm{B_s} \to \mu^+\mu^-) = (3.56 \pm 0.30) \times 10^{-9}$$

$$\text{MSSM: } \mathrm{BR}(\mathrm{B_s} \to \mu^+\mu^-) \propto \frac{\mathrm{m_b^2 m_t^2}}{\mathrm{M_A^4}} \tan^6\beta$$

$(B^0, B_s) \to \mu^+\mu^-$



LHCb + CMS: $BR(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$

Electric dipole moment d_e

$d_e < 8.7 \times 10^{-29}$ e · cm

ACME Collaboration, ThO

(SM phases: $d_e < 10^{-38}$ e · cm)

The unreasonable effectiveness of the standard model

arXiv:0905.3187

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1405.7875
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	m($\tilde{G}$)>10^{-4} eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$	275-440 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^{\pm}$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$	215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20	$\tilde{t}_1$	210-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$	260-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	700 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	420 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	285 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121}\neq 0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq 0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

10^{-1} — 1 — Mass scale [TeV]

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Triangle-2000 meeting 'Nonperturbative methods in field and string theory',
Copenhagen, June 21, 2000

WAGER ON SUPERSYMMETRY

for ten years ahead

QUESTION: Do you think that in ten years from now, that is by noon C.E.T. June 21st, 2010, at least one supersymmetric partner of any of the known particles will be experimentally discovered? [The term "discovered" means that it is universally recognized by the community, as judged by an independent committee of three wise men/ladies appointed by the sides.]

Please put your name (in block letters) accompanied by your signature in one of the three columns below, marked as "**yes**", "**no**" or "**abstained**".

By signing "yes" or "no" you promise to deliver a bottle (75cl) of good cognac at a price of not less than $50, in case you are wrong.

By signing "abstained" you acknowledge that you either do not care, or have not thought about it, but still you'd like to be informed in the year 2010 who has been a prophet ten years ago, and to gain the right to sheepishly participate in drinking the cognac purchased by those who have honorably lost the bet.

Your signature in one of the first two columns entitles you to ask for a copy of the present agreement.

The party of winners organizes a meeting of all involved in this wager not later than in June 2011. At this meeting the cognac bought by the losers will be jointly consumed.

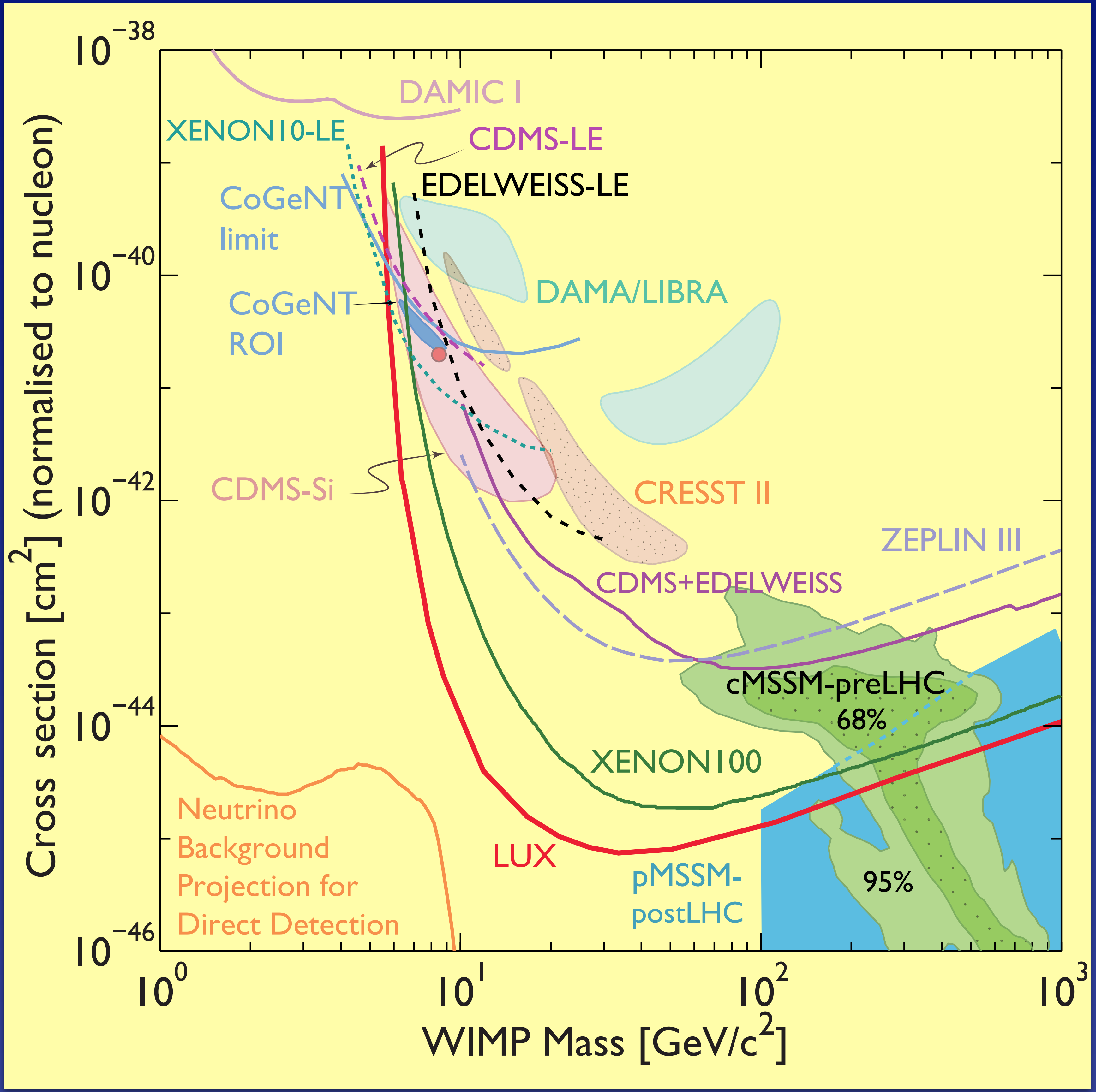
Yes, SUSY partners will be discovered	No, they won't	abstained
SEMENOFF	Peter Orland	MAKEENKO
[illegible]	Petrov	Neuberger
Kogan **	[illegible]	
Jan Ambjorn	FADDEEV	
A.Tseytlin	[illegible]	
D.S.Berman	G. 't Hooft *)	
Kimyeong Lee	G.C. Rossi	
	K. Yoshida	
	P.H. Damgaard	
	E. Kiritsis	
	J. Mishustin	
	I. Klebanov	
	M.A. Vazquez-Mozo	
	C. Hofman	
	Holger Bech Nielsen	
	[illegible]	

(continue signatures on the other side, if necessary)

*) But each side will claim victory

**) But it may be not as exciting as if neither SUSY, nor Higgs will be discovered.

Dark matter: direct searches



Dark matter searches and nucleon structure

Scale of SUSY expectations set by (spin-independent) σ

Neutralino WIMP: σ attributed to Higgs exchange

How does *H* interact with nucleon?

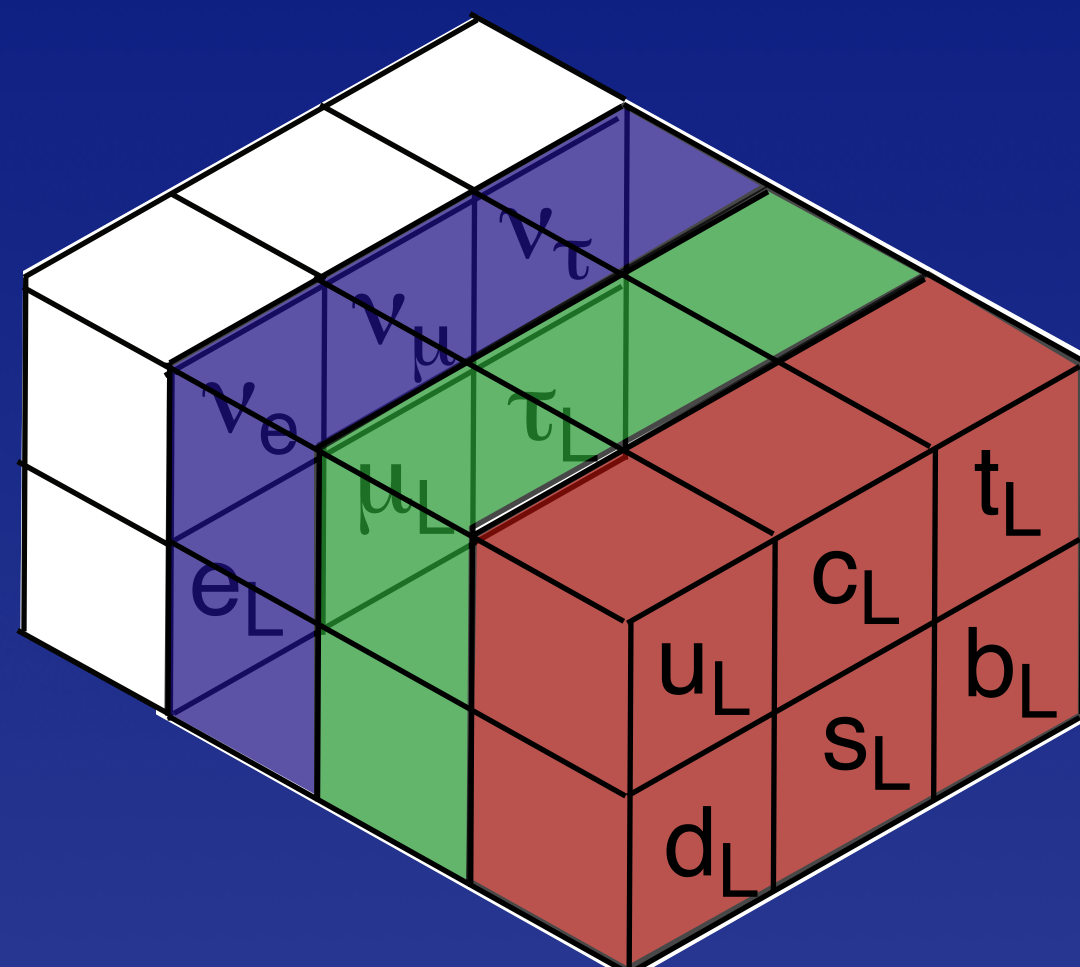
H coupling to heavy flavors: *s*, *b*, …

x 2-3 variation among lattice calculations

Experimental attention, perhaps theoretical reconception

A Unified Theory?

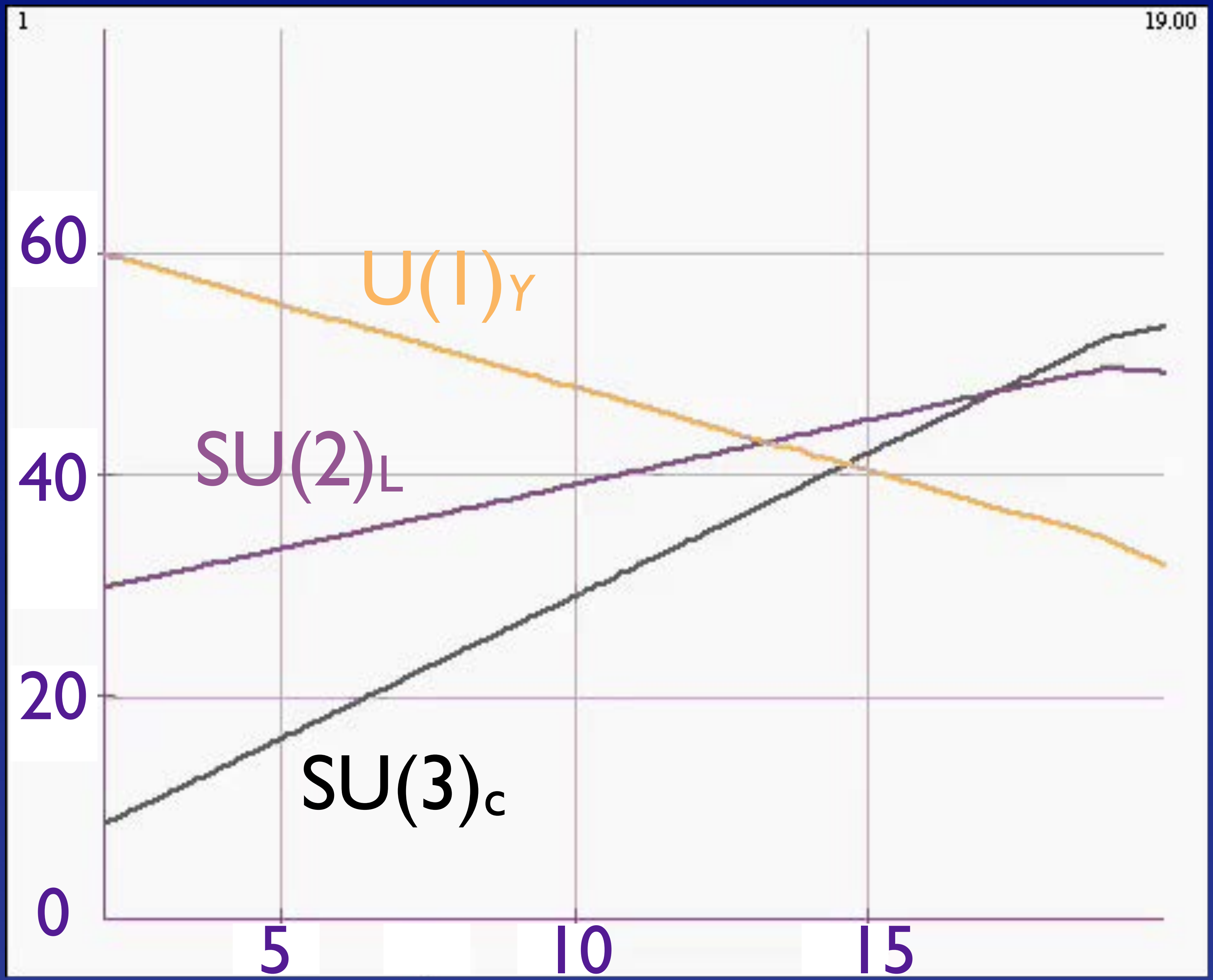
Why are atoms so remarkably neutral?



Coupling constant unification?

Extended quark–lepton families:
proton decay!

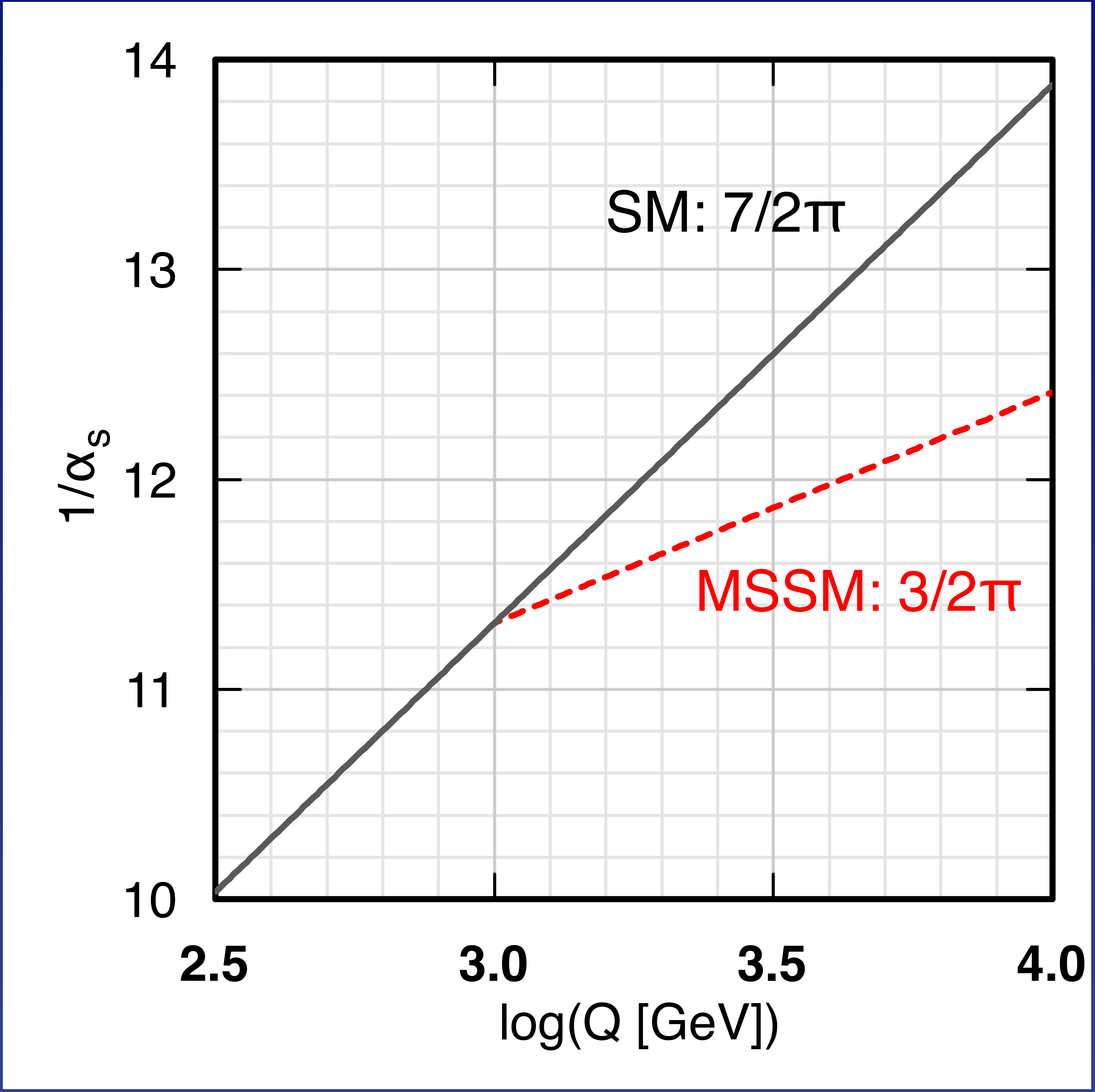
Unification of Forces?



$$\log_{10}\left(\frac{E}{1\ \mathrm{GeV}}\right)$$

$1/\alpha$

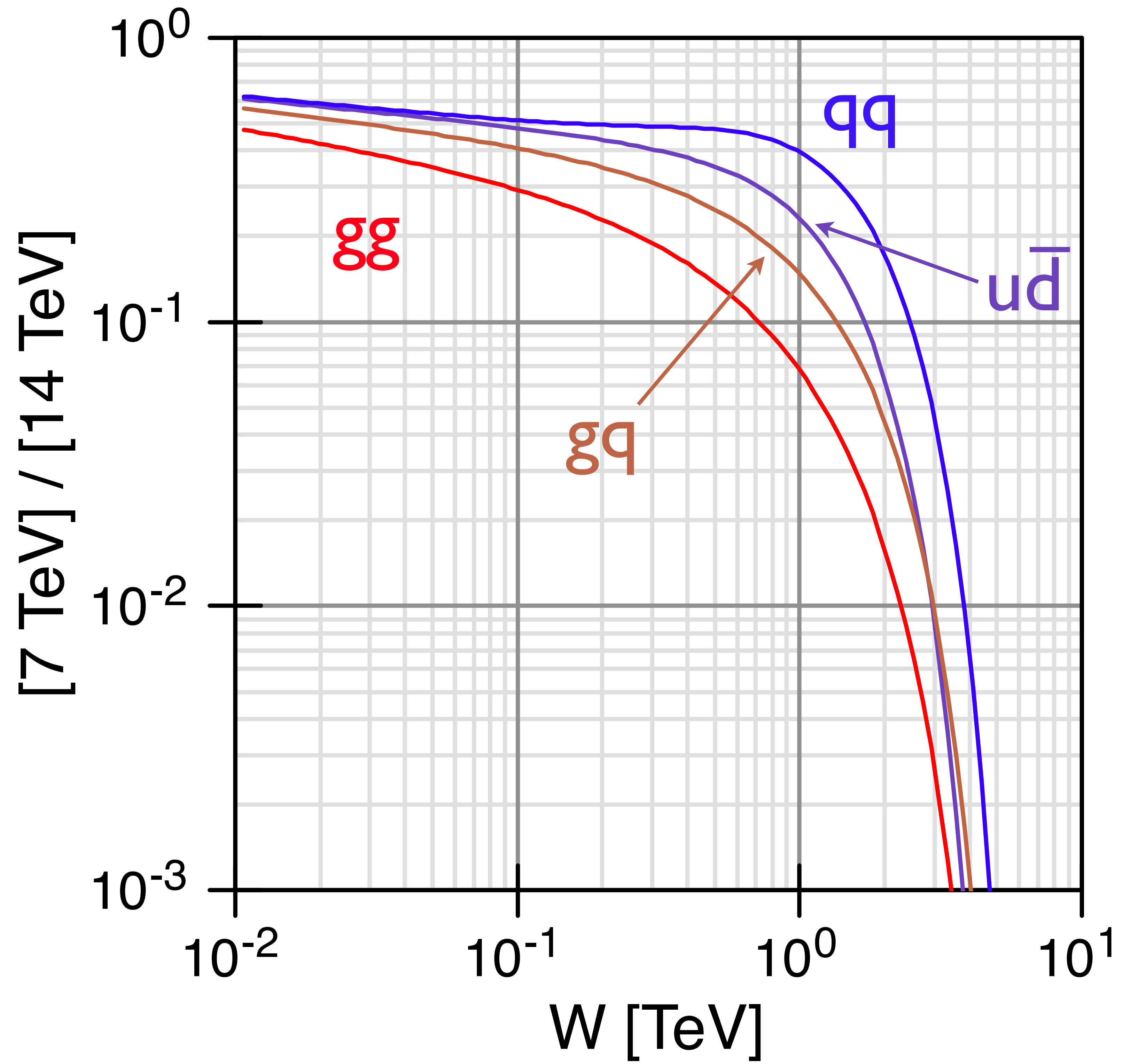
Might LHC see the change in evolution?



Wonderful progress …
… but miles to go:

LHC energy → 13 / 14 TeV
Luminosity x 100

Ratios of Parton Luminosities



Cf. Stirling

Issues for the Future (Now!)

1. What is the agent of EWSB? Is there a Higgs boson? Might there be several?
2. Is the Higgs boson elementary or composite? How does it interact with itself? What triggers EWSB?
3. Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons? *(How) is fermion mass related to the electroweak scale?*
4. Are there new flavor symmetries that give insights into fermion masses and mixings?
5. What stabilizes the Higgs-boson mass below 1 TeV?

Issues for the Future (Now!)

6. Do the different CC behaviors of LH, RH fermions reflect a fundamental asymmetry in nature's laws?
7. What will be the next symmetry we recognize? Are there additional heavy gauge bosons? Is nature supersymmetric? Is EW theory contained in a GUT?
8. Are all flavor-changing interactions governed by the standard-model Yukawa couplings? Does "minimal flavor violation" hold? If so, why?
9. Are there additional sequential quark & lepton generations? Or new exotic (vector-like) fermions?
10. What resolves the strong CP problem?

Issues for the Future (Now!)

11. What are the dark matters? Any flavor structure?
12. Is EWSB an emergent phenomenon connected with strong dynamics? How would that alter our conception of unified theories of the strong, weak, and electromagnetic interactions?
13. Is EWSB related to gravity through extra spacetime dimensions?
14. What resolves the vacuum energy problem?
15. (When we understand the origin of EWSB), what lessons does EWSB hold for unified theories? … for inflation? … for dark energy?

Issues for the Future (Now!)

16. What explains the baryon asymmetry of the universe? Are there new (CC) CP-violating phases?
17. Are there new flavor-preserving phases? What would observation, or more stringent limits, on electric-dipole moments imply for BSM theories?
18. (How) are quark-flavor dynamics and lepton-flavor dynamics related (beyond the gauge interactions)?
19. At what scale are the neutrino masses set? Do they speak to the TeV scale, unification scale, Planck scale, …?

20. How are we prisoners of conventional thinking?

?